

JOIDES RESOLUTION DRILL SHIP DRILL INTO INDIAN RIDGE MOHO
HOLE CLEANING STUDY

A Thesis

by

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MASTER OF SCIENCE

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ABSTRACT

The Integrated Ocean Drilling Program (IODP) uses a variety of technology for use in its deep water scientific research, including the Joint Oceanographic Institutions for Deep Earth Sampling (JOIDES) Resolution (JR) drill ship. The JR drill ship has been selected to core a deep basement hole. The goal is to core approximately 3000 meters below the seafloor in water depths approaching 700 meters. This borehole is estimated to reach and core the igneous lower crust and the crust-mantle transition. Previous expeditions have cored to depths approaching 1500 meters below the seafloor, so this goal is significantly deeper than previous attempts. While it is a capable vessel, the JOIDES Resolution does have several limitations, mostly related to the drilling fluid system. These limitations need to be understood and their effect on the operation addressed prior to the beginning operations.

The object of this study is to determine if the limitations, such as pumping and storage capabilities, will prevent the ship from being able to core to the desired depth. The first step will be to further define the limitations that are present in the given well plan. This will be done via analysis of drilling hydraulics and hole cleaning capability. From sensitivity analysis using WELLPLANTM, it was determined that the JR drillship will be able to provide hydraulics and hole cleaning capability to reach the upper mantle. Using WELLPLANTM, modeling was done for four different depths along the wellbore to determine the cutting volume concentration buildup, minimum flow rate required, and equivalent circulating density. By conducting sensitivity analysis on rate of penetration, pump rate, cutting diameter size, and cutting density, it was determined that the drill ship

has the capacity to properly clean the hole. After the hydraulics and hole cleaning have been evaluated, the next step is to come up with a viable mud program that can be used for the operation.

The end result is an analysis that not only determines if the geological coring of the crust and mantle transition can be accomplished but gives operational recommendations on how to achieve the stated goal with a minimal risk of drilling problems. With seawater being the main drilling fluid, it is recommended to add gel sweeps at regular intervals to ensure proper transportation of drill cuttings to the seafloor. It is also important to maintain sufficient pump rate, especially with larger sized cuttings or increased rate of penetrations. Using proper flow rate, rate of penetration, and gel sweep intervals will provide sufficient hole cleaning capacity for the JR drillship to core to the Moho.

DEDICATION

I would like to dedicate this thesis to my parents who have shown great support from across the Atlantic Ocean. Despite the time difference, you have shown the best encouragement I could ask for.

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1. INTRODUCTION

The Integrated Ocean Drilling Program (IODP) is an international marine research consortium whose goal is to study and answer many pressing scientific questions surrounding topics as varied as climate change, life sustainability in extreme environments and seafloor and near-seafloor geology and geophysics. In order to continue advancing the leading edge of scientific research of this type, IODP and their partners continuously work towards exploring in increasing depths and more extreme offshore environments. There are several industries that use drilling technology as an integral part of their business model including mining, geological exploration, and hydrocarbon exploration. The IODP leverages knowledge from all of these industries to try to achieve difficult tasks not typically undertaken by individual for-profit companies. One current objective of the IODP is exploring the composition of the near-seafloor geology, test the hypothesis that the Moho beneath the Atlantic Bank is a serpentinization front, and recover the igneous lower crust and the crust-mantle transition.

From previous exploratory coring, the composition of the lower crust has been found to consist mostly of gabbro, which are “coarse-grained mafic rocks commonly formed from slow cooling of magma chambers beneath mid-ocean ridges” (Wilson et al. 2006). Gabbros are equivalent in composition to basalt with the main difference being the grain size (King 2005a). **Fig. 1.1** shows how the general composition of basalt and gabbro both mainly consist of pyroxene (King 2005a). **Fig. 1.2** shows a picture of a 5 cm gabbro as well as an enlarged image of the sample (King 2005a). A current project of the

IODP is to retrieve core samples from the upper mantle of the Earth. This includes sampling the lower crust, transition into the Mohorovičić (Moho), and the upper mantle of the Earth. The Moho is the boundary between the crust and the mantle in the Earth. The Moho is defined as the depth where there is an acceleration in seismic wave velocity and chemical composition due to increasing density below the Moho (Lamontagne et al. 1999). **Fig. 1.3** shows the location of the Moho graphically between the lower density crust and the higher density mantle (Transocean 2009).

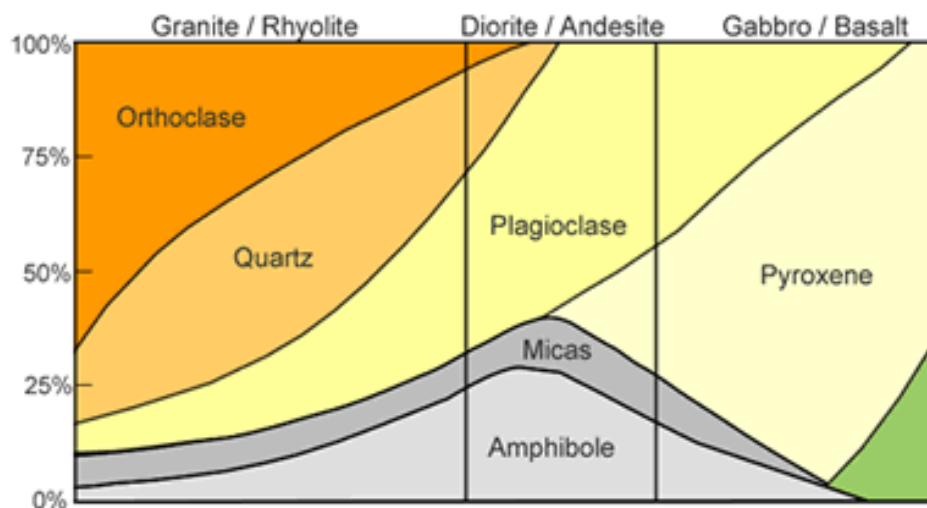


Fig. 1.1 – Generalized mineral composition of igneous rocks. Basalt and gabbro both consist mainly of pyroxene (King 2005a).



Fig. 1.2 – Picture showing a gabbro approximately 5 cm across with zoomed in picture approximately 1.3 cm across (King 2005a).

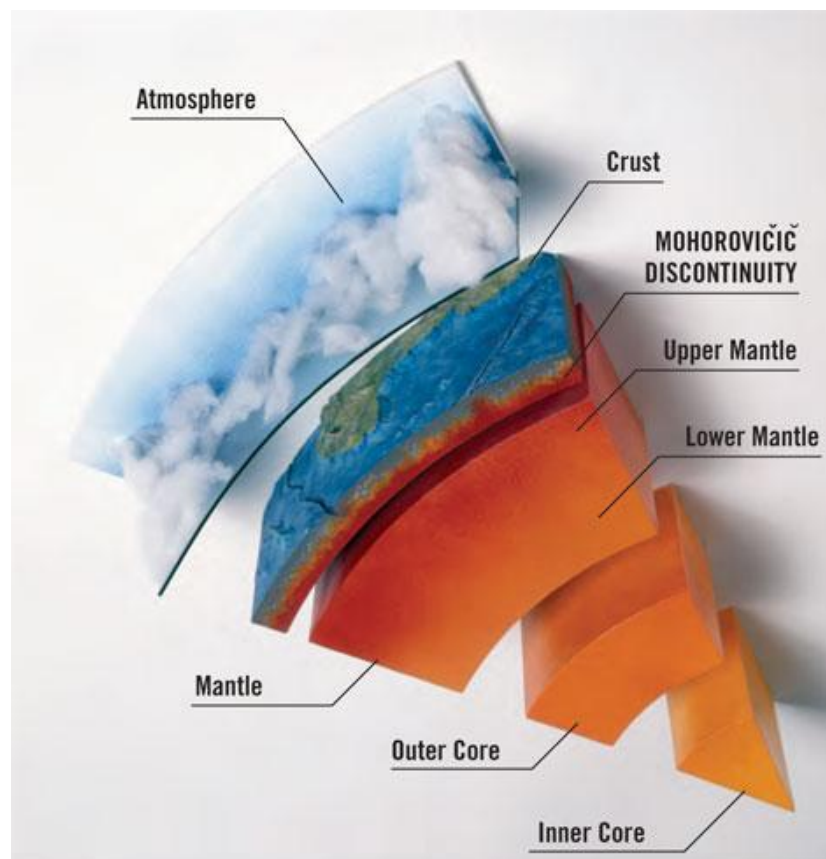


Fig. 1.3 – The location of the Moho is between the lower density crust and the higher density mantle (Transocean 2009).

1.1. Coring

The purpose of the exploratory drilling is to be able to understand the composition of the lower crust, moho, and mantle. The geological formations expected to be encountered include gabbro in the upper 1750 meters transitioning into ultramafic rocks including a mix of serpentized ultramafic rocks and gabbros (Storms 2014). Ultramafic rocks, or ultrabasic rocks, are igneous rocks that consist of very low silica content but are rich in minerals such as hypersthene, augite and olivine (King 2005b). **Fig. 1.4** shows basalt and gabbro rocks in ultramafic form with low silica content (King 2005a). In order to understand the composition of the crust, moho, and mantle, core samples need to be taken to compare with seismic studies conducted in the area. Commonly, core drilling is when a core bit cuts into the strata and a rock core is left in the central core conducting tube and carried to the surface (McGarr 1962). **Fig. 1.5** shows the procedure of obtaining a core sample and bringing it to surface (ESN 2009). This type of coring is typically done over a limited length of drilling and targets a specific formation interval within a formation. However a different type of coring process, known as continuous coring is expected to be used for this particular exploratory project. The continuous coring process creates minimal cuttings, relative to the standard coring methods and gives an understanding of the encountered formations through the distance drilled. Instead of sampling a select few formations, continuous coring allows for a much better understanding of the geology.

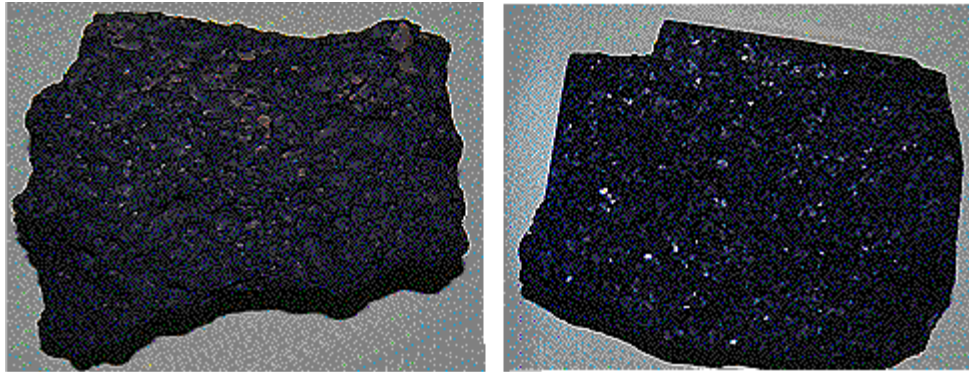


Fig. 1.4 - Ultramafic rocks with basalt rock on left and gabbro on right (King 2005a).

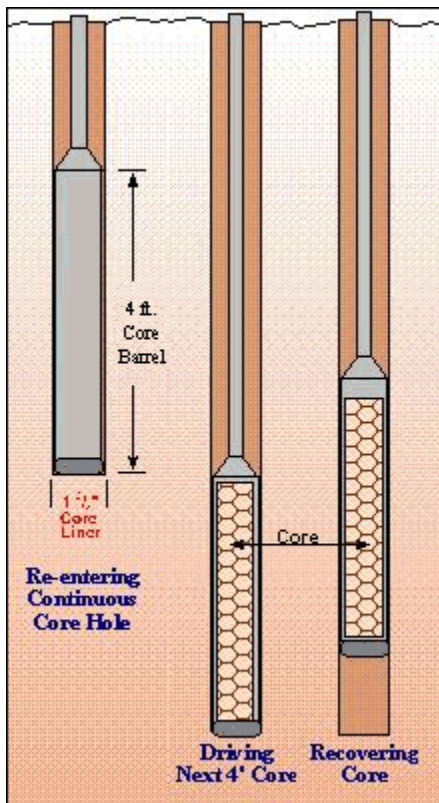


Fig. 1.5 - The procedure of obtaining a core sample and carrying it to the surface (ESN 2009).

The Integrated Ocean Drilling Program (IODP) has developed an instrumented drill collar for routine use in the program's global coring program (Myers et al. 2006). This instrument, which has been created to provide more real time data while drilling and coring samples, is what differentiates continuous coring from standard coring procedures. The drill collar improves the efficiency and recovery of core samples. The Drilling Sensor Sub (DSS) and Retrievable Memory Module (RMM), which are both part of the drill collar, are used to transmit real-time data to improve core recovery. **Fig. 1.6** shows how the DSS and RMM allows rapid retrieval of data acquired from the core barrel to the rig floor (Myers et al. 2006). By transmitting real-time data from the bit to the drill ship, adjustments in weight on bit (WOB), revolutions per minute (RPM), etc. can be continuously monitored and changed to optimize the performance. Continuous coring is performed by retrieving the core barrel at regular intervals (usually every 9.5 meters) (Myers et al. 2006). The retrieval of the core barrel is done by lowering an empty core barrel to the BHA, then advancing 9.5 meters before pulling the full barrel to surface using wireline retrieval system (Myers et al. 2006). The barrel is then emptied before being deployed to get the next coring sample. By using the described drill collar, more of the rock will be intact in the core sample which leaves minimal cuttings that needs to be cleaned out of the hole.

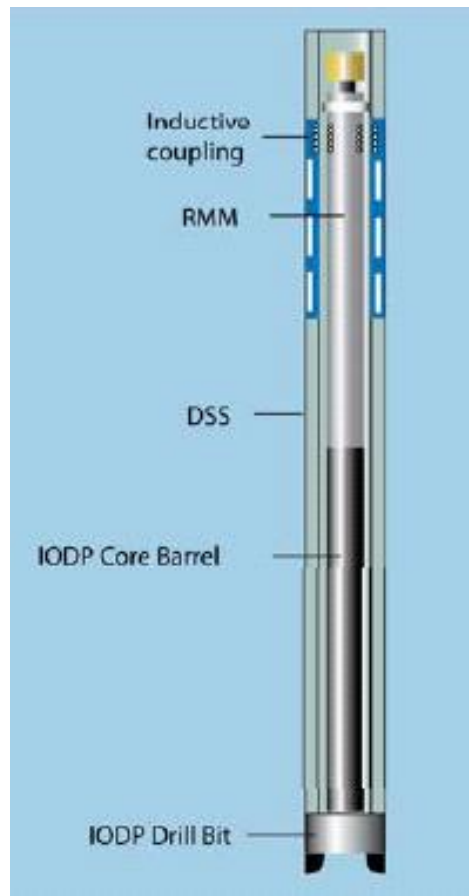


Fig. 1.6 – The DSS and RMM acquire drilling dynamics data near the bit (Myers et al. 2006).

When using a drill ship, retrieving core samples can cause difficulties as the waves can cause variations in WOB and drill string movement during coring (Kidd 1979). The inherent stability of an anchored platform provides a drilling rig many advantages over a drillship, which must use thrusters in conjunction with geopositioning to remain steady. A fixed installation rig is usually unaffected by the waves that cause fluctuations on WOB, while a drill ship is very affected by these waves. With the previously noted drill collar that was developed by IODP, the fluctuation in waves can

be monitored by transmitting real-time data from the bit, allowing the dynamic parameters of the drill string to be recorded both on the drill ship floor and at the drill bit when coring (Myers et al. 2006). This will allow the driller to continuously change the WOB to improve the sampling conditions in the hole while encountering different weather. Using IODP's drill collar will allow for better quality core samples which will be carried to the surface using wireline system. The cores can then be collected and analyzed to give an understanding of the subsurface geology.

1.2. Slim-hole drilling

Conventional drilling refers to drilling large hole diameters with several casing strings set to reach total depth. As production of hydrocarbon requires a large diameter hole to allow economic flow rate and rapid production, larger production casing is better. Slim-hole drilling refers to drilling a smaller hole with the stated goal of reducing drilling equipment and fluid requirements as well as the number of casing strings, and may result in a smaller diameter for the production casing. For the project at hand, production is not a consideration as no hydrocarbons are expected to be encountered and thus fewer casings strings will be placed in the hole. **Fig. 1. 7** shows a comparison of a conventional well and a slim-hole well (Bode et al. 1991). As can be seen in Fig. 1. 7, the starting diameter is significantly smaller for the slim-hole well (8.5 inches) compared to the conventional well (17.5 inches). For the IODP project at hand, the slim-hole drilling method will be implemented to reduce expenses.

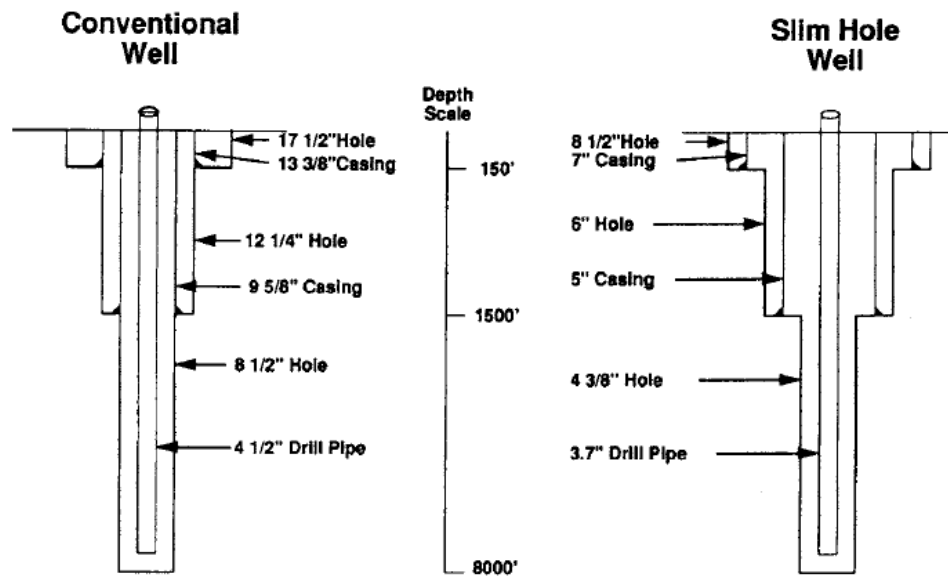


Fig. 1. 7 – Example of conventional vs. slim-hole well (Bode et al. 1991).

When designing a slim-hole well, it is very important to carefully consider hydraulics as they affect a small hole much more than they do a conventional hole due to reduced annular clearance. The main requirements that need to be considered for the hydraulics are the cutting entrainment, wellbore stability, optimum bit performance, and minimum mud power consumption (Delwiche et al. 1992). With the slim-hole drilling, comes a smaller annular clearance which makes the design of hydraulics more important. Slim-hole drilling's limited clearance in the annulus makes the wellbore stability, bit performance and cutting entrainment more affected than when using conventional drilling. A slim-hole well experiencing a kick needs to be detected much sooner than for conventional drilling, as the height of the kick increase significantly for a slim-hole drilling with a smaller annulus. As the JR drill ship has storage capacity

limitations, drilling slim-hole will be the best approach for the given project. This will take less mud product storage place as well as potentially reduce mud pumping requirements.

Circulation rates of mud required for slim-hole drilling need to be carefully considered, primarily because of the high annular velocity in the small annular space and the lifting of finer cuttings (Walker and Millheim 1990). When coring, there will be significantly less cuttings compared to drilling, so a lower velocity will be required to lift the cuttings. Field data collected in 1990 shows that more than 12,200 meters of slim hole continuous core drilling was used with recovery rates more than 98% of the rocks sampled (Walker and Millheim 1990). Based on the technology and results from that study, it is clear that the continuous core method should provide sufficient rock to analyze from the sea floor all the way through the lower crust, moho, and into the upper mantle.

1.3. Riserless drilling

Riserless drilling with weighted mud systems, commonly referred to as “Pump & Dump” drilling strategy, is an established drilling technique used on deepwater wells with shallow hazards (Akers 2011). Although the project well is not considered to be in deepwater (1500 meters or above), it is being drilled with the riserless method due to mud storage and treatment limitations on the JR. It should be noted that extensive seismic research in the area has proven that there are likely no hydrocarbons to be encountered, so it is anticipated the entire well will be able to be safely drilled with the riserless method (Schubert 2014).

When riserless drilling with prepared drilling fluids, the fluid is used to make one circulation in the well before being discharged at the seafloor (Akers 2011). Therefore it is important that the prepared drilling fluid is biodegradable and non-toxic, as it will be released into the environment. **Fig. 1.8** shows a schematic of the seafloor return drilling strategy from a rig (Cohen et al. 2010). As no fluid will be returned to the drilling vessel, large volume of fluids is required for this drilling strategy. One method of allowing more drilling fluids to be handled at offshore locations is to blend a higher density weighted mud than required, and “cut-back” the higher density drilling fluid with seawater while on location (Akers 2011). This will allow for larger volumes to be available while drilling. Since the drilling vessel will be drilling riserless, it is important to determine if the storage capacity of the vessel is large enough for the expedition and how often consumables must be resupplied.

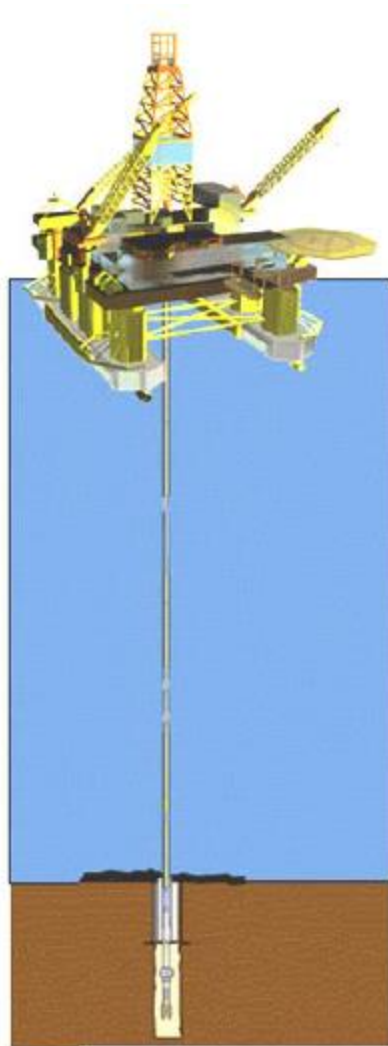


Fig. 1.8 – “Pump & Dump” drilling strategy of returning mud to seafloor (Cohen et al. 2010).

The research vessel JOIDES Resolution (JR) has been the workhorse for scientific research since 1985, having drilled 2,236 wellbores in over three decades (IODP 2013). As the drillship was commissioned in 1985, several limitations exist which need to be considered when planning exploration projects. One of the limitations

of the drillship is the fact that it cannot drill in shallow water (less than 100 meters) (Burger and Fujioka 2006). Fortunately, at the proposed location, the sea depth is 700 meters, so this limitation will not prevent the exploration of the mantle. A significant limitation that might cause a problem is the storage capacity of the drillship. The JR drill ship has a storage capacity of 3,700 bbls while a 6th generation drill ship built in 2011 has a storage capacity of 22,000 bbls (Claassen et al. 2011). With the limited storage space, hole-cleaning and wellbore stability need to be evaluated to determine if the drillship will be feasible for the given project.

The IODP has also developed core bits for exploratory drilling. A core bit is a drilling tool with a hole through the center that removes sediment rock and allows the core pedestal to pass through the bit and into the core barrel (Graber et al. 2007a). This tool is important in geological exploratory drilling to receive sufficient cores that can be analyzed for changes in formation below the seafloor. There are different types of core bits used including advanced piston corer (APC), rotary core barrel (RCB), and advanced diamond core barrel (ADCB) (Graber et al. 2007a). **Fig. 1.9** shows a rotary core barrel (RCB) that will be used in the aforementioned project.

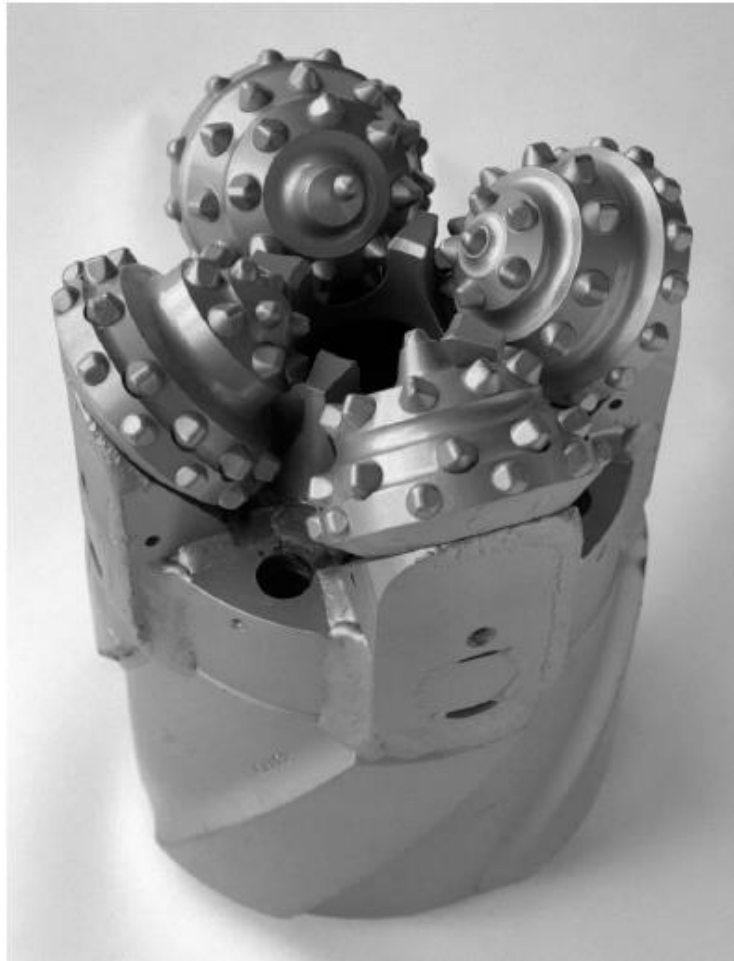


Fig. 1.9 – Rotary core barrel (RCB) four roller cone bit (Graber et al. 2007a).

The RCB inner core barrel free falls while pumping fluid through the drill string and latches into the RCB bottom-hole assembly (BHA) (Graber et al. 2007b). The RCB is designed to recover core samples from firm to hard sediments, which is why it will be used for drilling through gabbro. The inner core barrel holds 9.5 meter core samples with 2.312 inches core diameter and is retrieved using wireline operations. **Fig. 1.10** shows a schematic of the RCB coring system (Graber et al. 2007b).

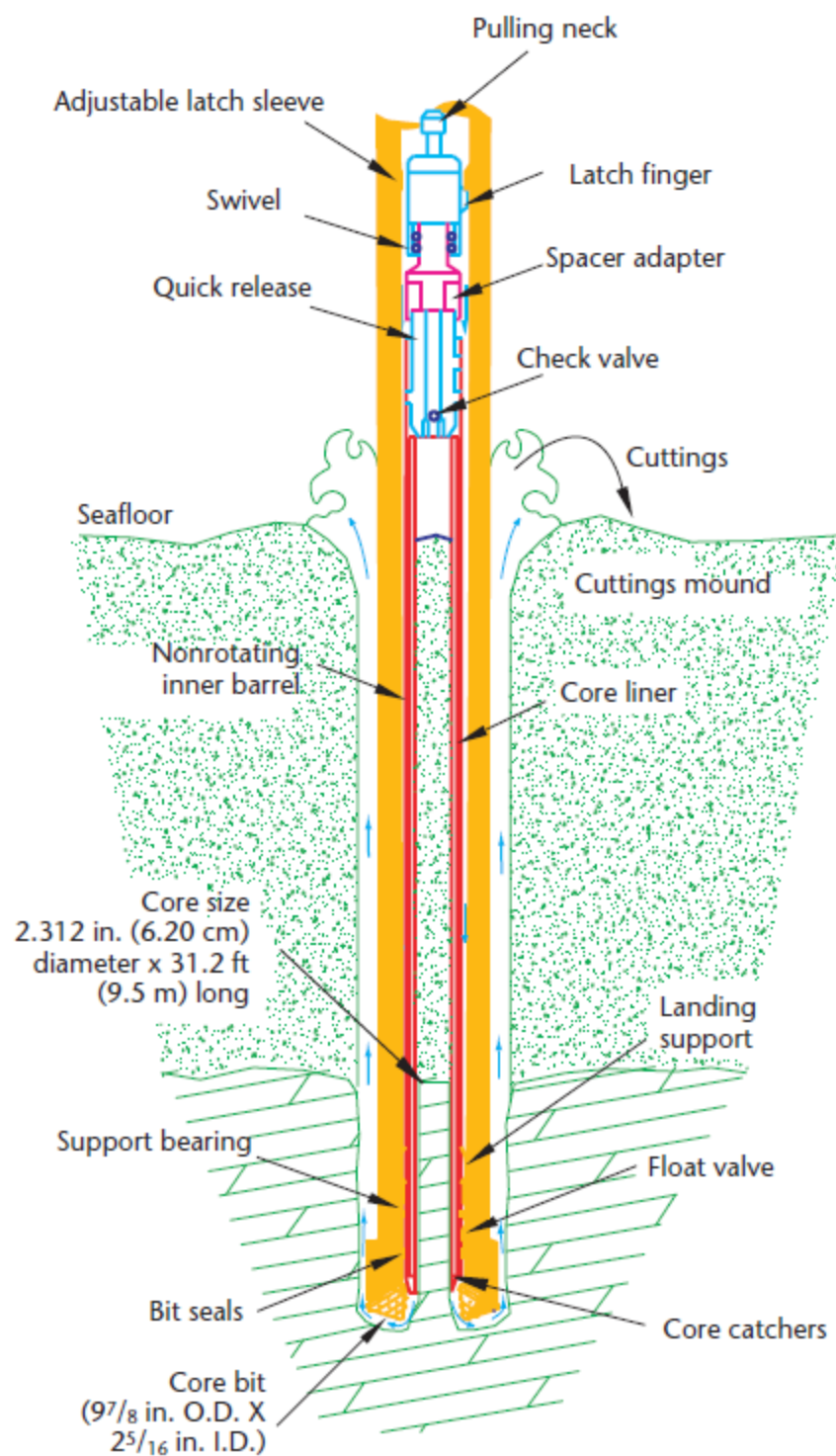


Fig. 1.10 – Schematic of RCB coring system in coring mode (Graber et al. 2007b).

1.4. Drilling fluid

Selecting the proper drilling fluid is important for the success of a drilling operation (Bleier 1990). The drilling fluids serve several functions including: removing cuttings from wellbore, cooling and lubricating the bit, controlling formation pressures, and maintaining wellbore stability (Devereux 1999). Drilling fluid composition varies based on the demands of the wellbore. For this project, the most important factors that need to be considered are environment, high pressure and temperature, well trajectory, and economics.

Due to the various requirements of environmental and political regulation encountered throughout the world, the available drilling fluids may be severely limited. As pump and dump returns the drilling fluid to the seafloor, the drilling fluids need to be designed to fit all the requirements for the area. Additional factors complicating this fluid selection are that the fluid must carry sufficient cuttings, provide the necessary bit cooling, lubrication, and hydrostatic control previously mentioned. As it is present in the project environment prior to drilling activity and available in vast quantities seawater makes an economic and environmentally neutral option. It is anticipated to be the main drilling fluid for the project and will be coupled with high-viscosity mud sweeps used for extra cleaning. A sweep is a relatively small volume of liquid (10-80 barrels) of a viscous fluid, typically a carrier gel, that is used to circulate and remove debris and cutting left in the hole (Schlumberger 2014).

Relatively high temperatures are expected for the wellbore. The temperature gradient expected is 3-5°C per 100 meters in the upper section of the hole and increasing

to potentially 10°C per 100 meters in the lower section of the hole (Storms 2014). With the given information, temperatures of 200-250°C are expected, with a maximum, yet highly unlikely, temperature of 300°C possible. The tools required for drilling the hole should not have problems at these temperatures, but the drilling fluid will need to be designed to withstand high temperatures. As seawater will be the base drilling fluid, additives that can create higher viscosity and withstand the high temperatures need to be determined to use for sweeps to better clean the hole.

Attapulgite is a non-swelling clay mineral that create high surface area, high porosity particles when thermally activated (Haden 1963). This creates a gel-like substance when mixed with seawater that creates a low shear rate viscosity for efficiently lifting cuttings. The attapulgite has proven very stable at high temperatures and will be a good additive for sweeps when cleaning the hole (Carney and Meyer 1976). The attapulgite structure consists of a two-dimensional layer structure more closely related to the chainlike structures of the amphiboles than are other clay minerals (Haden 1963). Sepiolite is another clay mineral that is very similar in composition to attapulgite. Gels were created using attapulgite and sepiolite separately and tested under high pressures to determine stability. Temperatures exceeding 300°C were tested in an effort to crystalize the gels, but as all attempts at crystallization failed it can be assumed that the additives will be stable at the expected conditions downhole (Haden 1963).

With the vertical trajectory of the well and the economic benefits of using seawater, the seawater with gelled sweeps will meet all the requirements for the aforementioned project. If mud weight needs to be increased for pressure control, barite

can be added to the drilling fluid. Barite is a mineral consisting of barium sulfate and is used as a weighting agent in drilling fluids. To mitigate barite's tendency to settle out of fluid downhole, one of the clay minerals needs to be added to the mixture when using barite for weighting up. By using seawater, attapulgite or sepiolite, and barite the requirements of using environmental friendly fluid, countering high temperatures and pressures, maintaining well trajectory, and keeping fluids economical will be fulfilled.

1.5. Well control

Well control is the process of using pressure and physical barriers to prevent or mitigate influxes of fluids from subsurface formations. Well control systems include, but are not limited to, mud pumps, surface kick-detection system, blowout preventers (BOP's), drilling fluids, and a driller that knows what he is doing (Bode et al. 1991). The primary kick-detection system is a gain in the trip tank. With slim-hole drilling, this gain can be substantially smaller (1 bbl vs 15 bbl) than in conventional drilling when detecting a kick (Bode et al. 1991). This gain in volume indicates that some reservoir fluid most likely entered the annulus. Fortunately for the explorative drilling planned in the IODP project, hydrocarbons are not anticipated be present in any of the formations (Schubert 2014). The extensive seismic testing done to detect the possibility of hydrocarbons has given IODP a high degree of confidence that there will be no hydrocarbons encountered while drilling the well. Since there is no need to monitor drilling fluid returns or other kick-detection systems to prevent well control incidents, the fluid can discharge to the seafloor during the drilling of the entire well.

The primary method of well control is the hydrostatic pressure exerted by the drilling fluid, which makes the design of drilling fluid and mud pumps important when planning a well (Vujasinovic 1986). In event of primary control loss, sudden increase in pressure or loss of circulation, a secondary control function, the blowout preventer (BOP), is necessary to prevent uncontrollable flow from formations (Vujasinovic 1986). There are several types of blowout preventers, but the purpose of any design is to prevent uncontrolled hydrocarbon flow to the surface. **Fig. 1.11** shows a typical BOP used in the North Sea (Holand 1991). As previously mentioned, extensive research has been conducted of the area, and there will be no hydrocarbons at the area of interest. The need for a BOP is therefore non-existent as a secondary control of hydrocarbon flow will not be needed. The focus of the well control needs to be on the drilling fluid and mud pumps to maintain the hydrostatic pressure of the hole.

From test data, it has been determined that approximately 90% of the pump pressure is lost in the annulus for slim-hole drilling (Bode et al. 1991). Because annulus pressure loss is significant in the slim-hole drilling, dynamic kill becomes an effective well control method (Bode et al. 1991). The dynamic kill is a well control method used to stop a blowout and kill a well (Abel 1996). By increasing the equivalent circulating density (ECD), the well can be killed. To increase the ECD at the bottom of the hole, the pump rate is increased. The dynamic kill is the most efficient method of stopping an influx in slim-hole drilling using the annular frictional pressure drop thus minimizing the pressure exerted on the casing shoe. To implement the dynamic kill, additional pressure should be put on the formation by increasing pump rate (Bode et al. 1991). By increasing

pump rate quickly, the influx volume is minimized and the well can be killed without exceeding the pressure for the casing shoe.

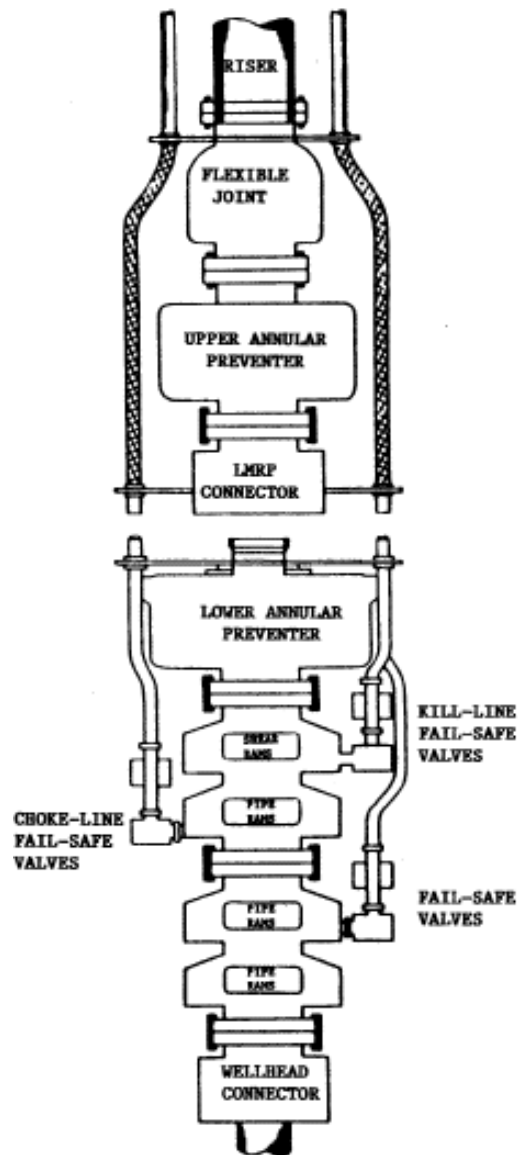


Fig. 1.11 – One type of blowout preventer (BOP) used in the North Sea (Holand 1991).

2. PROBLEM STATEMENT / SCENARIOS

The objective of this study is to determine the feasibility of the JOIDES Resolution (JR) drillship undertaking the drilling operation of reaching the upper mantle. To complete this study, different scenarios have to be developed and reviewed. As the JR has limited storage capacity for large quantities of drilling mud, the amount of sea water drilling mud and special additive drilling mud must be determined. The hydraulics required for pumping fluid and cleaning the hole also need to be considered. The first stage to be examined is the drilling to 1750 meters below sea floor (mbsf). This is the expedition's first objective and the primary concern in this hole section is whether or not the hole can be cleaned properly. The second stage will attempt to reach a total depth (TD) of 3000 mbsf. The bottom hole assembly (BHA) has been designed to accommodate both stages, but the drilling mud required and intervals of sweeps will vary between the two stages. The last part of this section covers the storage capacity and hydraulics available at the drillship.

2.1. Bottom hole assembly (BHA) design

The bottom hole assembly (BHA) is the lower part of the drill string consisting of the coring bit, drill collars, subs, and core barrel. This part of the drill string will remain constant for the drilling operation during the two expedition stages. As the core samples will need to be able to reach the drillship from the BHA, every section of the drill string needs to be designed with an inner diameter (ID) equal to or greater than 4 ¼ inches (104.70 mm). This means that the drill pipe connections have to be designed specifically for these conditions. The IODP has therefore made special equipment for

previous expeditions that will also be used during this operation. The BHA will be built in the following order:

- 9 7/8 inch RCB core bit
- Bit sub
- Outer core barrel
- Top sub
- Head sub
- 10 joints of 8 1/4 inch drill collar
- Tapered drill collar
- 6 joints of 5 1/2 inch drill pipe
- Cross over from 5 1/2 inch to 5 inch drill pipe

The graphical illustration of the BHA in **Fig. 2.1** is easier to follow for this composition.

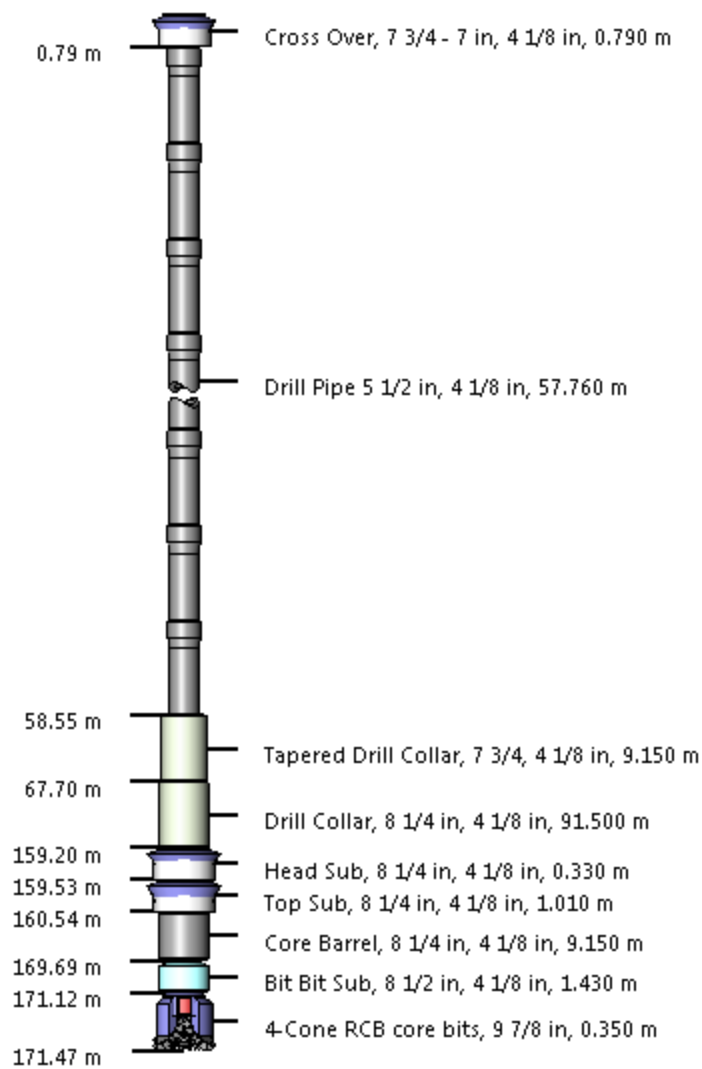


Fig. 2.1 – Graphical illustration of the bottom hole assembly (BHA).

2.2. First entry scenario to 1750 mbsf

The primary scenario evaluated is the first re-entry into the hole, with a target of 1750 mbsf. The drill string for this section consists of the BHA displayed in Fig. 2.1 with 5 inch drill pipe for the remainder of the drill string. The drill pipe size is one of the

parameters that will be changed to determine the best situation for hole cleaning. Error!
Reference source not found. **Fig. 2.2** shows a graphical representation for the drill string described. In addition to the targeted 1750 meters below the seafloor, the drill string must also extend through 700 meters of seawater to reach the seafloor.

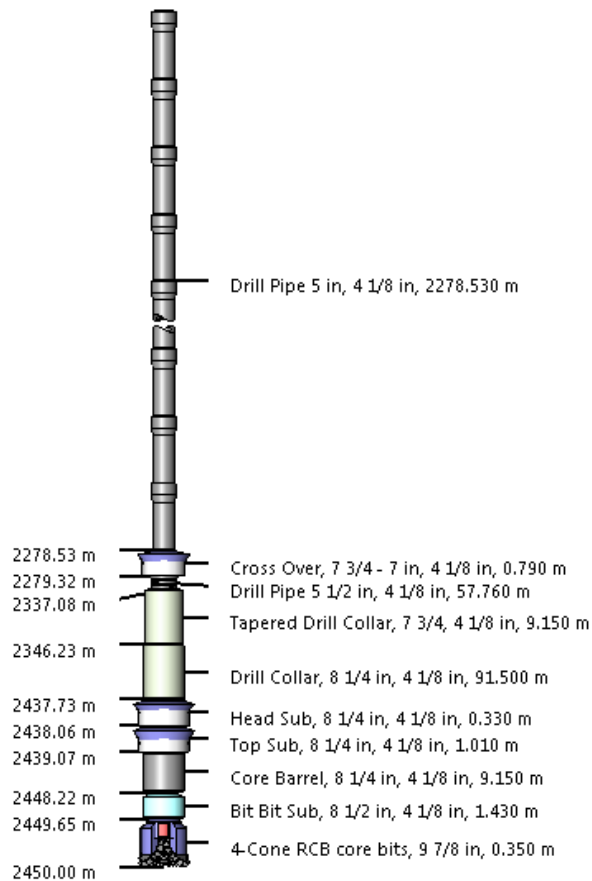


Fig. 2.2 – Drill string to 1750 mbsf, including 700 m of drill pipe in water, not to scale.

When determining parameters for the given model, there will be additional simulations executed halfway to the desired depth of 1750 mbsf. The first of the two cases will simulate drilling at 875 mbsf (total length of 1575 meters drill string). The next case will simulate drilling at a depth of 1750 mbsf (2450 total length). These simulations consist of varying several parameters including:

- drill pipe size (cross over between 5 inches and 5 ½ inches)
- Rate of penetration (ROP)
- Pump rate
- Cutting characteristics (cutting density and size).

Based on the simulated results, recommendations will be provided for each depth which was studied.

2.3. Second entry scenario to TD at 3000 mbsf

The second scenario has a target depth of 3000 mbsf. This will be the most important section to model as larger quantities of drilling fluid will be required to clean the entire section drilled. As temperatures close to 300°C are expected, the sweeps must be designed to be compatible with a seawater drilling fluid. With the increasing temperature, seawater can expand, thus reducing its ability to carry cuttings out of the well. As the capacity of the drillship is limited, and use of a mud-storage supply boat is

prohibitively expensive, seawater is the most economical drilling fluid. For this to be possible, the drilling fluid must be carefully designed to ensure the hole still gets cleaned properly.

For the second entry, the drill string will once again consist of the BHA described in Fig. 2.1 as well as 5 inch drill pipe extending from top of BHA to drill ship. Again, the simulations will be of the hole halfway between first entry and TD, 2375 mbsf (3075 meters total length.) The second model simulation will be at TD of 3000 mbsf (3700 meters total length.) **Fig. 2.3** shows a graphical representation of the drill string to total depth. Based on simulations, variations of the following will be explained in later sections:

- Drill string size (5 or 5 ½ inch)
- Rate of penetration (ROP)
- Pump rate
- Cutting characteristics

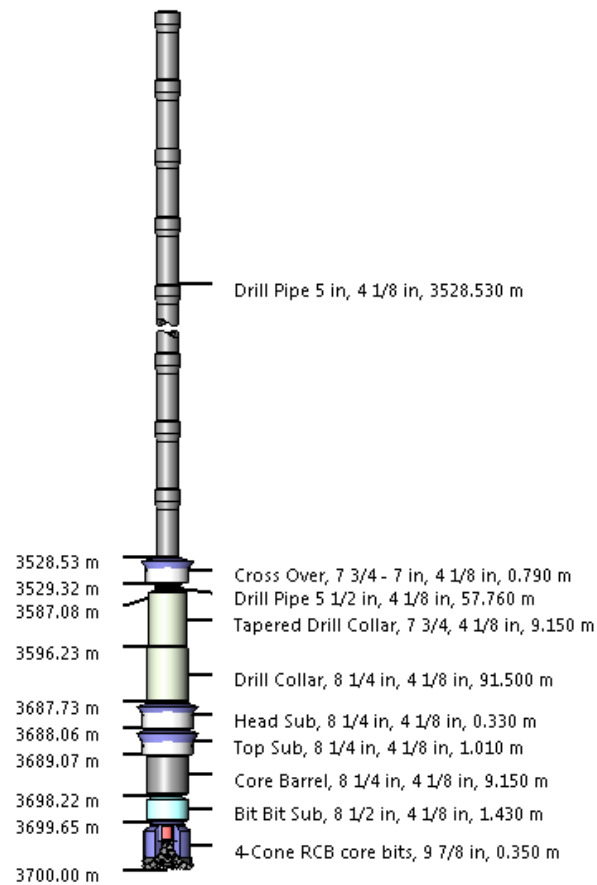


Fig. 2.3 – Drill string to 3000 mbsf, including 700 m of drill pipe in water.

2.4. JOIDES Resolution capacity

The JOIDES Resolution drill ship is equipped with six mud pits and dual triplex mud pumps. The mud pits have a total capacity of 3,714 bbls. Mud pits 1 and 2 hold 786 bbls each, pits 3 and 4 hold 317 bbls, and pits 5 and 6 hold 754 bbls each. **Fig. 2.4** shows a schematic of the available mud pits with the capacity indicated for each of the pits. The reason the mud is separated into several pits is to give the JOIDES Resolution the ability

to maintain several different muds separately until they are mixed for specific purposes. For the given expedition, a dual triplex National Oilwell 1700 mud pump with 6 ½” liners will be used. Each of the triplex pumps available is capable of continuously pumping 120 strokes per minute, with 5.17 gallons per stroke at 90% efficiency.

PIT # 6	PIT #4	PIT # 2
WT=	WT=	WT=
VIS=	VIS=	VIS=
BBLS.	BBLS.	BBLS.
S.T.	S.T.	S.T.
CAP = 754Bbls.	CAP = 317Bbls.	CAP = 786Bbls.
PIT #5	PIT # 3	PIT # 1
WT=	WT=	WT=
VIS=	VIS=	VIS=
BBLS.	BBLS.	BBLS.
S.T.	S.T.	S.T.
CAP = 754Bbls.	CAP = 317Bbls.	CAP =786Bbls.

Fig. 2.4 – Schematic of the available mud pits on JOIDES Resolution with the capacity indicated for each of the mud pits (Storms 2014). The different pits allows for different muds to be prepared and made available at the same time.

3. OBJECTIVES AND PROCEDURE

The objective of this study is to determine if the JOIDES Resolution has the capacity to drill to the upper mantle. For this to be accomplished, Halliburton's Landmark WELLPLAN™ program was utilized to analyze different parameters with respect to drilling hydraulics and hole cleaning. At each of the aforementioned scenarios, different parameters were varied and results analyzed to determine the hole cleaning efficiency and system pressure loss at different depths. As cuttings are created at the bit, there are different transportation mechanisms used to transport the cuttings to the surface (SPE 28306). For nearly vertical wells, which is what will be encountered in IODP's operation, particle settling is the primary transportation problem encountered. It is therefore important to ensure that the drilling fluids and hydraulics are designed to transport these cuttings out of the hole by countering the settling velocity as well as adding transportation velocity.

3.1. Equivalent circulating density

Equivalent circulating density (ECD) is the effective fluid density including the frictional circulating pressure and the hydrostatic pressure change. It is referenced to a certain depth and is important to consider when designing a well. ECD is calculated using **Eq. 1**, which depends on the hydrostatic pressure (**Eq. 2**) as well as the frictional pressure change (**Eq. 3**). Landmark's WELLPLAN™ calculated the ECD to make sure that the pressure exerted by the drilling fluid stay between the pore pressure and the fracture pressure. By maintaining ECD in the range or window between pore pressure

and fracture pressure, kicks will be prevented while at the same time losses will not be induces.

$$ECD = \frac{P_h + P_f}{0.052 D_{tvd}} \dots \dots \dots \text{Eq. 1}$$

$$P_h = 0.052 W_{mud} D_{tvd} \dots \dots \dots \text{Eq. 2}$$

$$P_f = \sum \frac{\Delta P}{\Delta L} \Delta D_{md} \dots \dots \dots \text{Eq. 3}$$

The ECD calculation is used to make sure the circulating pressure stays between the pore pressure and fracture pressure. It is important to stay within this operational window to avoid fluid loss or fracturing. With excessive fluid pressures during circulating, maintaining the ECD will be more difficult. **Fig. 3.1** shows an example of the operating window between the pore pressure and fracture gradient (Oakley and Conn 2011). The given example used displayed a very small operating window as the fracture gradient was estimated to be very close to the pore pressure. To determine the fracture gradient of a formation, some data must be available. Common methods of determining fracture gradient prediction are from leak-off tests, limit tests, or formation breakdown tests (Kit 2007). Unfortunately, for the planned wellbore, this information is not available. Therefore, it is important to minimize the effect of fluid pressure while circulating to avoid fracturing the rocks.

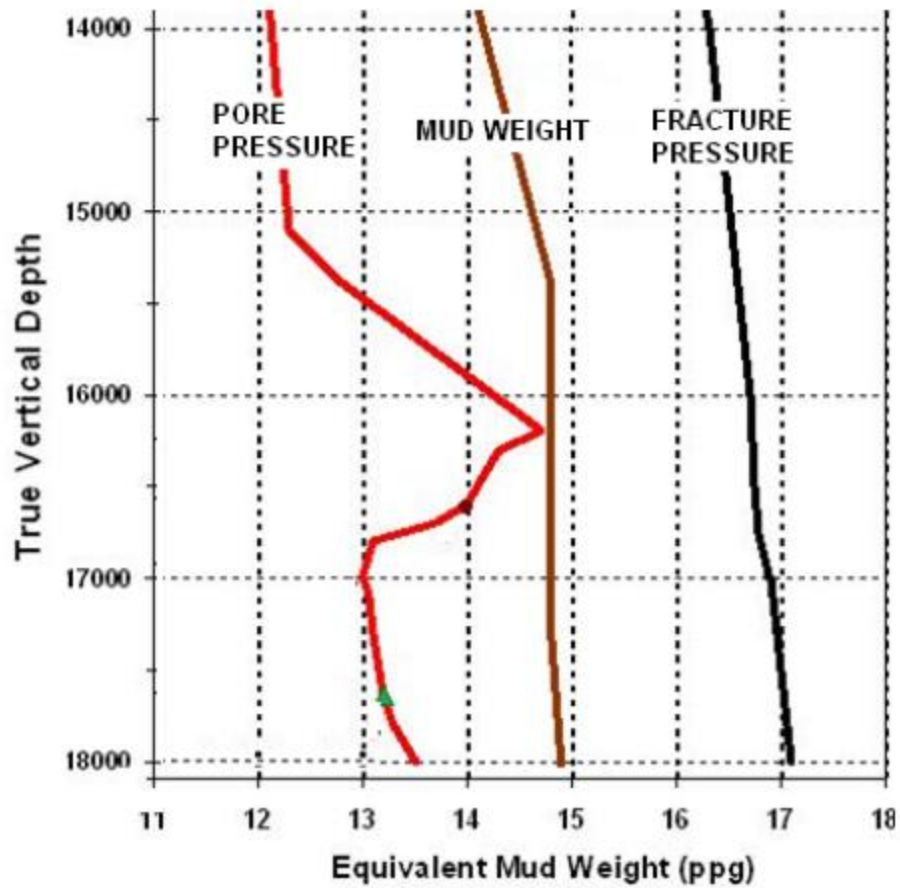


Fig. 3.1 – Example of operating window between pore pressure and fracture gradient (Oakley and Conn 2011).

As previously mentioned, it is important to minimize the effect of the pressure exerted by fluid circulating. It is difficult to determine the operating window for a wildcat well with no information available for the location. Therefore, WELLPLAN™'s assumed pore pressure and fracture pressure is found using **Equation 4**.

$$P = D_{tvd} \times EMW \times 0.051948 \dots\dots\dots \text{Eq. 4}$$

The difference between the pore pressure and the fracture pressure is the equivalent mud weight, EMW. For pore pressure, the EMW is assumed to be 8.6 ppg, or 1031 kg/m^3 , while for fracture pressure, the assumed EMW is 9.0 ppg, or 1078 kg/m^3 . As this is the assumed inputs for WELLPLAN™, a pore pressure of 1031 kg/m^3 ECD will be assumed for this well and a maximum fracture gradient of 1078 kg/m^3 . As there are no hydrocarbons expected for the area in which the expedition drilling, the operating window will not be as strict on the pore pressure side. For the gabbro that is expected to be encountered, the permeability will be very low which will reduce the chances of influx with low ECD's. There still exists the possibility of wellbore stability issues should the ECD drop below the pore pressure, however gabbro is relatively competent rock making these concerns minimal.

3.2. Volume suspended

It is well known within the oil and gas industry that when drilling vertical wells, the annular mud velocity must exceed the settling velocity of cuttings to ensure transportation of cuttings to surface (SPE 28306). As such, it is important to determine how the concentration of suspended cuttings in the annulus. The amount of suspended cuttings is calculated from annular velocity and slip velocity of the cuttings. Annular velocity is the speed at which fluids move in the annulus. Cutting slip velocity is the velocity of the cuttings as they fall due to the effect of gravity and density. The annular velocity is calculated using **Equation 5** while the slip velocity of cuttings is calculated using **Equation 6** or **Equation 7**. If the annular velocity is less than 53 ft/min, the slip velocity is calculated using **Equation 6**, while if the annular velocity is equal to or

greater than 53 ft/min, **Equation 7** is used. These equations are taken from the API Standards 13D (API 2003).

$$V_a = \frac{24.5Q}{D_H^2 - D_P^2} \dots\dots\dots \text{Eq. 5}$$

$$V_{slip} = 0.00516V_a + 3.0006 \dots\dots\dots \text{Eq. 6}$$

$$V_{slip} = 0.02554(V_a - 53) + 3.28 \dots\dots\dots \text{Eq. 7}$$

From the calculated velocities, the fluid transportation ratio can be determined. **Equation 8** is used to calculate the transportation ratio. WELLPLAN™ displays this ratio as a percentage of volume suspended. If the annular velocity is less than the settling velocity, and the fluid transportation is negative, the cuttings are settling and the hole is not being cleaned properly. If the annular velocity is greater than the settling velocity, and the fluid transportation is positive, the hole is being cleaned. The lower the volume of cutting suspended, the longer it will take for cutting concentration to build up. If the cutting volume suspended is high, then cutting will build up around the bit making it difficult to drill ahead. **Fig. 3.2** shows the concept of annular velocity and cutting slip velocity.

$$F_T = 1 - \frac{V_{slip}}{V_a} \dots\dots\dots \text{Eq. 8}$$

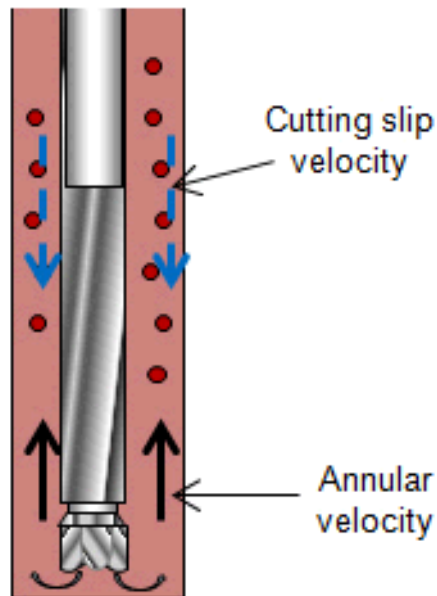


Fig. 3.2 – Good hole cleaning have higher annular velocity than cutting slip velocity (Lapeyrouse et al. 2011).

3.3. Minimum flow rate

The minimum flow rate, also called the critical flow rate, is the flow rate that needs to be maintained to prevent the buildup of a cuttings bed. In horizontal wells, this flow rate is much larger and more complicated than in vertical wells, as the main transportation for cuttings in horizontal wells are rolling then lifting versus lifting in vertical wells. The rule of thumb for determining the flow rate in horizontal wells is for the velocity to result in approximately 60 m/min, or 200 ft/min (SPE 15417). This is significantly larger than the rule of thumb for vertical wells which is 31 m/min, or 100 ft/min (SPE 15417). To calculate the minimum flow rate required to lift the cuttings out of the hole, the rheological model has to be considered. For saltwater, the Newtonian

rheological model can be used, while for the gel sweeps the Herschel-Bulkley rheological method should be used. The difference between the Newtonian fluid and Herschel-Bulkley fluid is that the flow behavior index, n , has a constant value of 1 for Newtonian fluid and is calculated using **Equation 9** for the Herschel-Bulkley fluid (Guo and Liu 2011). **Equation 10** calculates the yield stress that needs is an input for **Equation 9** (Guo and Liu 2011).

$$n = 3.322 \log \left(\frac{\theta_{600} - \tau_y}{\theta_{300} - \tau_y} \right) \dots\dots\dots \text{Eq. 9}$$

$$\tau_y = 2\theta_3 - \theta_6 \dots\dots\dots \text{Eq. 10}$$

Another difference between the two models is that the fluid consistency index, K , must be calculated for the Herschel-Bulkley fluid using **Equation 11** while the Newtonian fluid has a constant consistency index of 0 (Guo and Liu 2011).

$$K = 500 \frac{\theta_{300} - \tau_y}{511^n} \dots\dots\dots \text{Eq. 11}$$

The mathematical differences between the two models are a result of different fluid behavior when put under stress. In a drilling application, the primary difference between the models is that the Newtonian fluid has no gel strength, or yield point. The lack of gel strength means that the fluid does not require extra pressure to start circulation, but it also means that the fluid is unable to suspend cuttings under static conditions. The Newtonian fluid relies solely on the fluid velocity to overcome the particle slip velocity of the cuttings while the Herschel-Bulkley fluid exhibits a yield point, thus have a gel-strength. **Fig. 3.3** shows the presence of a yield point, the y-intercept, of the Herschel-Bulkley model, while the Newtonian fluid pass through the

origin. The yield point shows that the Herschel-Bulkley fluid will suspend cuttings under static conditions, when no circulation is applied.

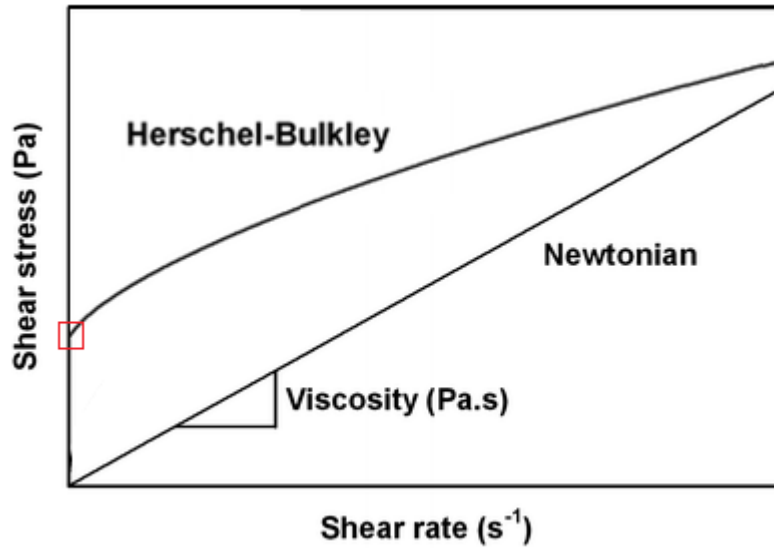


Fig. 3.3 – The difference between a Newtonian fluid and a Herschel-Bulkley fluid. The Herschel-Bulkley fluid shows a yield point within the red square, while the Newtonian fluid passes through the origin.

When the fluid consistency index and the fluid behavior index are calculated, WELLPLANTM calculated the dimensionless flow rate using **Equation 12**. From this, the critical or minimum flow rate can be calculated using **Equation 13**.

$$Q_{gb} = Q \left[8 \times \frac{n}{\frac{2(1+2n)}{(a)^{\frac{1}{b}}}} \right]^{\frac{1}{2-(2-n)b}} \times \left[1 - \left(\frac{r_p}{r_h} \right)^2 \left(1 - \left(\frac{r_p}{r_h} \right)^{\frac{b}{2-(2-n)b}} \right) \right] \dots\dots\dots \text{Eq. 12}$$

$$Q_{crit} = r_h^2 \left[\frac{\rho g b^{\frac{1}{b}} r_h^{\left(\frac{1}{b+n} \right)}}{K \rho^{\left(\frac{1}{b-1} \right)}} \right]^{\frac{b}{2-b(2-n)}} Q_{gb} \dots\dots\dots \text{Eq. 13}$$

WELLPLAN™ displays this critical flow rate as the minimum flow rate in m³/min. It is important to maintain this minimum flow rate to ensure proper cleaning of the hole at any given time.

3.4. Rheological properties

For the saltwater gel sweeps, it is important to determine the rheological properties to use for the Herschel-Bulkley model. As a rule of thumb, the yield point should be 1.5 times the hole size, in this case 20-25 (Lanthier 2014). The yield point can be calculated using **Equation 14** (API 2003).

$$YP = 2\theta_3 - \theta_6 \dots\dots\dots \text{Eq. 14}$$

For the yield point to be calculated, rheological data must be input into WELLPLAN™. As this data is not available for the salt gel sweeps to be used, data from a field test of sepiolite was used (Carney and Meyer 1976). Based on the readings in **Table 3.1**, the inputs for WELLPLAN™ were created. The inputs in WELLPLAN™ require readings at 600, 300, and 3 rpm. To determine the inputs for WELLPLAN™, the data received while drilling Expedition 305, Hole 1309D was used to match the standpipe pressure. By modeling the hole in WELLPLAN™, **Fig. 3.4** shows that the standpipe pressure from WELLPLAN™ is approximately 250 psi higher than the results from the expedition. The fact that it is a constant difference means we can make the assumption that this a fixed pressure drop within the system. Thus, the simulated results can be adjusted by this constant pressure. The rheological properties were modeled based on the standpipe pressure and the values in Table 3.1 and determined to be 100, 85, and 50 for readings at 600, 300, and 3 rpm respectively. With these values the yield

point is calculated as 23, which matches the desired value for a 9 7/8 inch hole. Another variable that needs to be altered is the density of the fluid. Sepiolite and attapulgite is expected to add some density to the fluid, so an estimated density of 1046 kg/m³, or 8.7 ppg, is used for the given model.

Table 3.1 – Rheological data for sepiolite drilling fluid (Carney and Meyer 1976).

Reading	20 °C	400 °C
AV	37.5	65.5
600 reading	75	131
300 reading	50	89
PV	25	42
YP	25	47
200 Reading	49	70
100 Reading	44	46
6 Reading	30	15
3 Reading	20	12

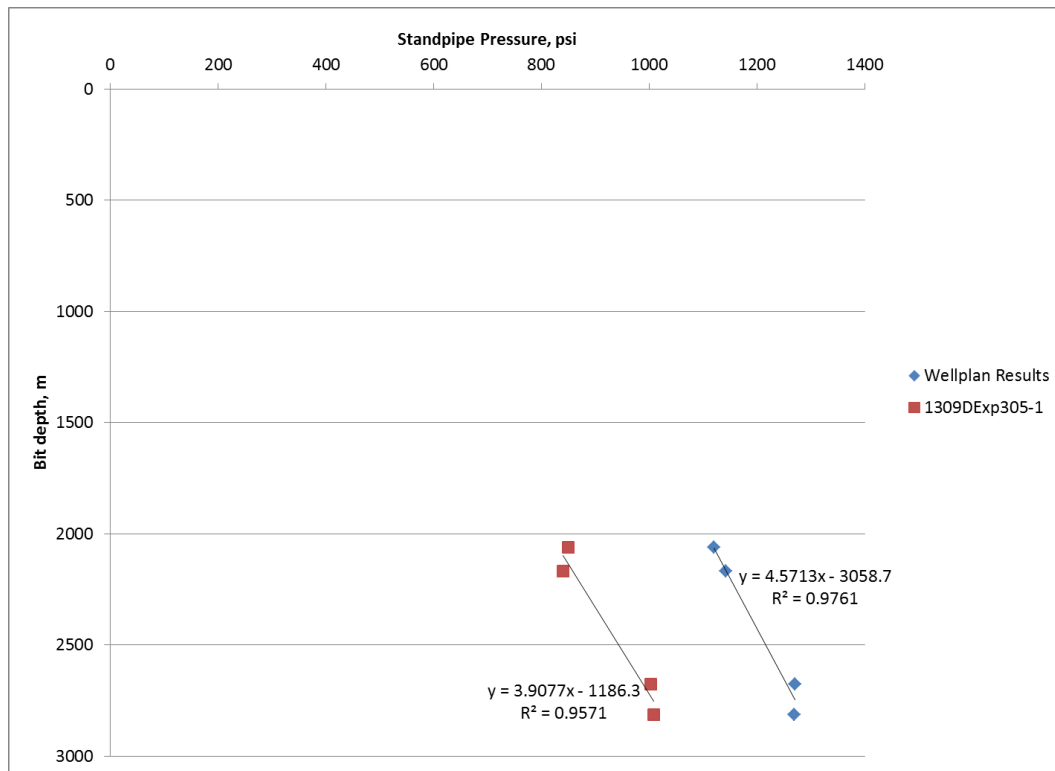


Fig. 3.4 – Standpipe pressure for Expedition 305 Hole 1309D have a pressure difference from WELLPLAN™ of 250 psi. The pressure difference can be accounted for pressure losses that are not considered in WELLPLAN™.

4. RESULTS

To model the scenarios of hole cleaning at 875, 1750, 2375, and 3000 mbsf, base values had to be determined in order to create a sensitivity analysis. For the rate of penetration (ROP), the base value used was 2.5 m/hr based on previous coring exploration in similar fields (Bleier 1990). The pump rate was determined based on the operating conditions of the National Oilwell 1700 triplex mud pumps. The base pump rate was assumed to be for one pump at 120 strokes/min at 90% efficiency for a rate of 2.348 m³/min. The base case for cutting density was determined using densities of typical rocks and minerals (Alden 2014). The range of gabbro densities listed was given as 2.70 – 3.50 SG, with the average being 3.03 SG. Looking at basic igneous rocks, which are expected to be encountered at greater depths, the range of density is 2.09 – 3.17 SG with an average of 2.79 SG. The base case for cutting densities was valued at 3.0 SG with the intention of varying the density to below 2.0 and above 3.5 SG. Finally, the cutting diameter was difficult to assign a base value as the previous expeditions have also used returns to seafloor. As the cutting diameters were not given, the values recommended by WELLPLAN™ were used. WELLPLAN™ specified a normal range as 0.1 to 0.25 inches, or 2.54 to 6.35 mm. The base case of 5 mm was used for simplicity reasons. The values are summarized in **Table 4.1**.

Table 4.1 – Values used as base case for WELLPLAN™ modeling.

Variable	Value	Units
Rate of Penetration	2.5	m/hr
Pump Rate	2.348	m3/min
Cutting Density	3.00	SG
Cutting Diameter	5.00	mm

4.1. Base case saltwater results

The base case for the equivalent circulating density (ECD) is modeled at 3000 mbsf using the operating parameters in Table 4.1 and saltwater as the drilling fluid, and is displayed in **Fig. 4.1**. The ECD gradually increase with increasing depth until the BHA, where the ECD sharply increases.

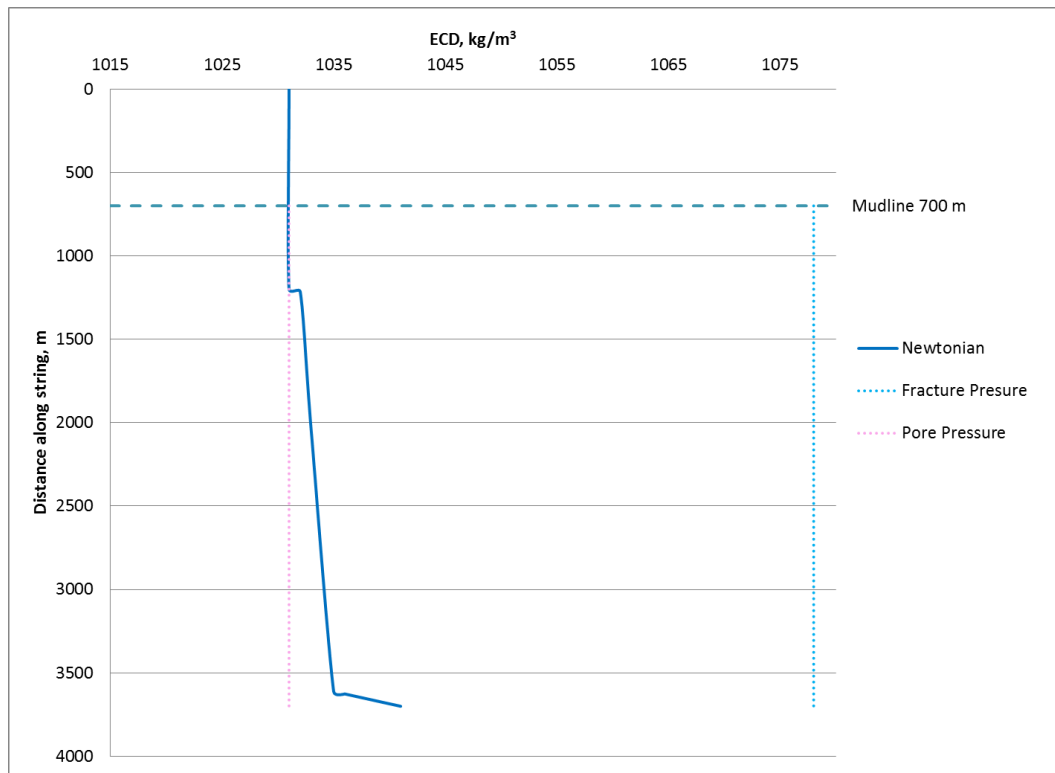


Fig. 4.1 – Base case using parameters in Table 4.1 show that the ECD increases slightly with increasing depth, but remains well within the operating window. The curve shows a gradual increase until the BHA, where the ECD shows a sharp increase.

The minimum flow rate required to prevent cuttings concentration buildup for the base case is with saltwater is shown in **Fig. 4.2**. Following a slight decrease in minimum flow rate due to difference in casing and open hole size, the minimum flow rate remains constant until the BHA is encountered. The required flow rate decrease sharply across the BHA due to the smaller annular clearance.

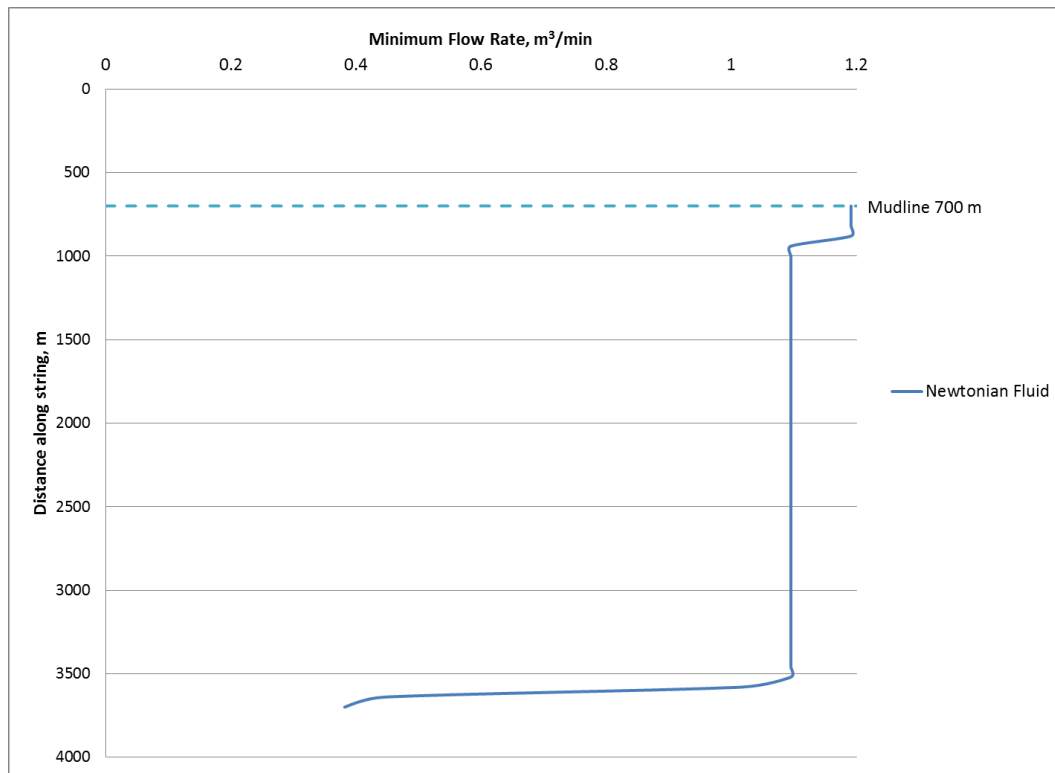


Fig. 4.2 – The minimum flow rate required to prevent cutting build up slightly decrease right below the seafloor when the annular diameter decreases from the casing to open hole. The minimum flow rate then remains constant until the BHA, where the flow rate sharply drop as the velocity required to clean the annulus decrease.

The volume suspended value is used to determine how efficient the defined parameters are at cleaning the hole. A low volume suspended means the annulus has a low percentage of cuttings left to clean, while a high percentage of volume suspended means the cutting concentration is developing faster. A rapidly increasing cutting concentration can prevent the bit from drilling ahead due to cuttings collected at the bit.

Fig. 4.3 shows the result of volume suspended using saltwater, a Newtonian fluid.

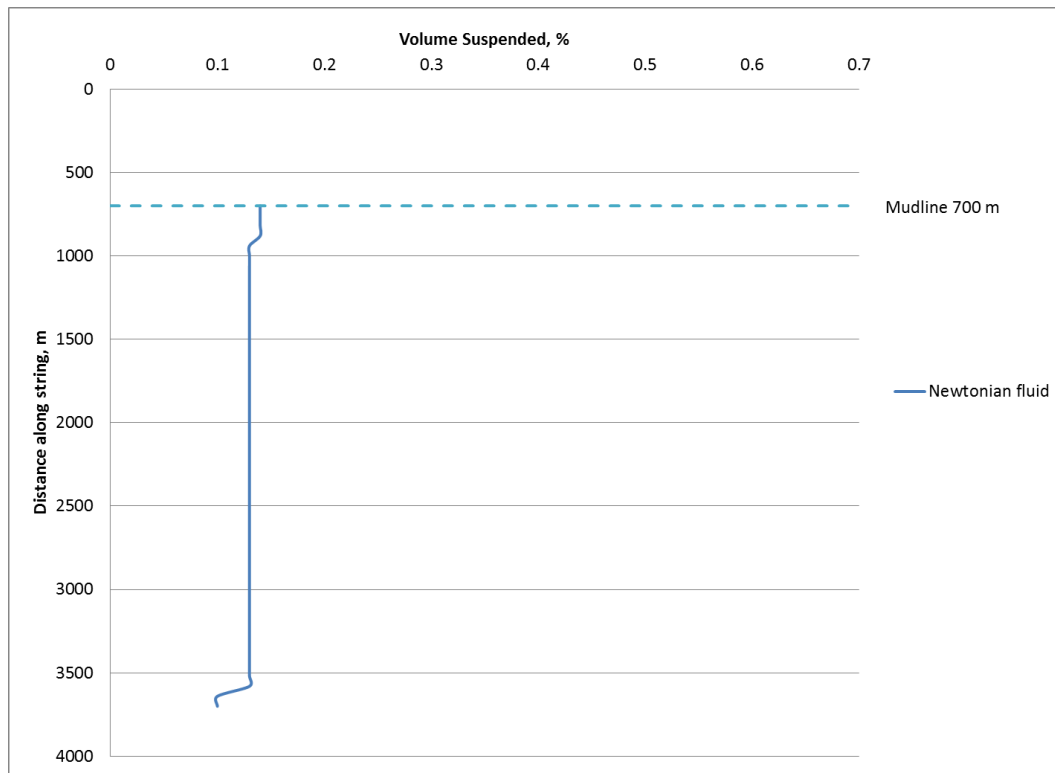


Fig. 4.3 – Using base value parameters the volume suspended in the annulus while circulating using saltwater is between 0.1 to 0.2%. That means the cutting concentration is developing very slowly while circulating.

The geometry of the drill pipe affects the minimum flow rate required to clean the hole sufficiently at increasing depths. **Fig. 4.4** shows that when using 5 ½ inch drill pipe, the minimum flow rate is lower than when using 5 inch drill pipe. Fig. 4.4 also show that the minimum flow rate remains constant for ROP's up to 20 m/hr, then increase linearly with increasing ROP's.

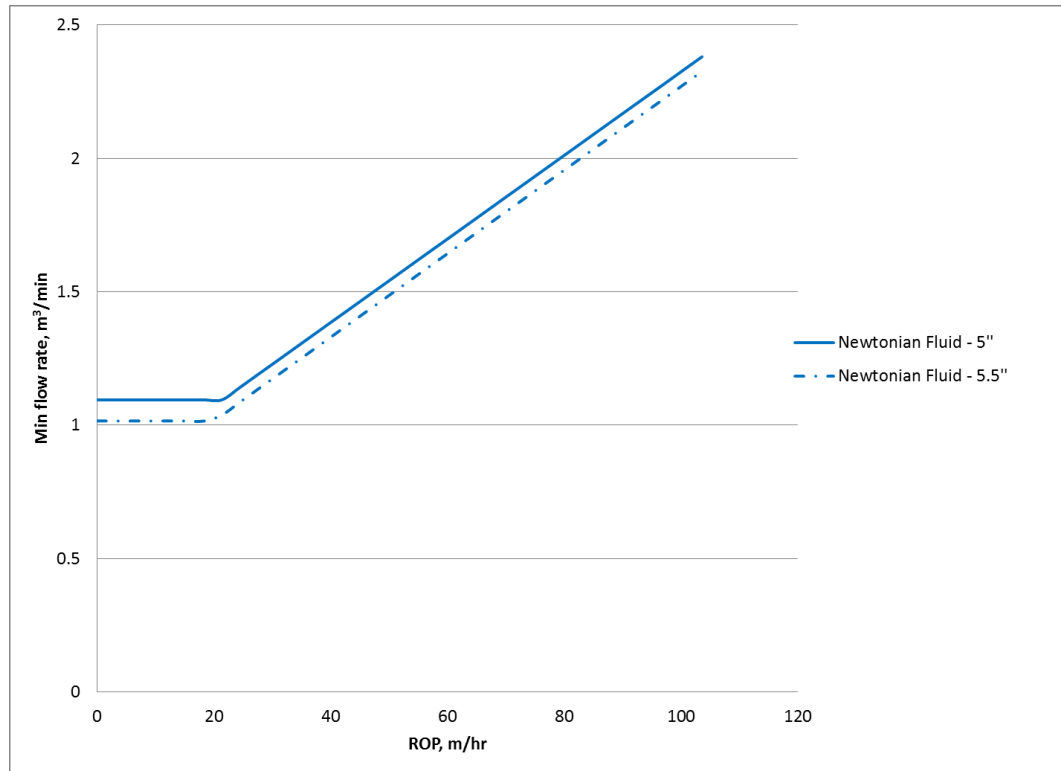


Fig. 4.4 – The minimum flow rate required to clean the hole remains constant for ROP's up to 20 m/hr, but then increase linearly. The 5 inch drill pipe also requires a higher flow rate than the 5 ½ inch drill pipe at all different ROP's.

4.2. Base case gel sweeps results

The base case also needs to be modeled for gel sweeps, which must be added to create gel strength for suspension during static conditions. The ECD for the gel sweep is shown in **Fig. 4.5** which shows that the ECD increase faster for the gel sweeps than it does for the saltwater. The ECD increase across the BHA is lower in comparison to the saltwater, but overall the ECD increase is more distinct.

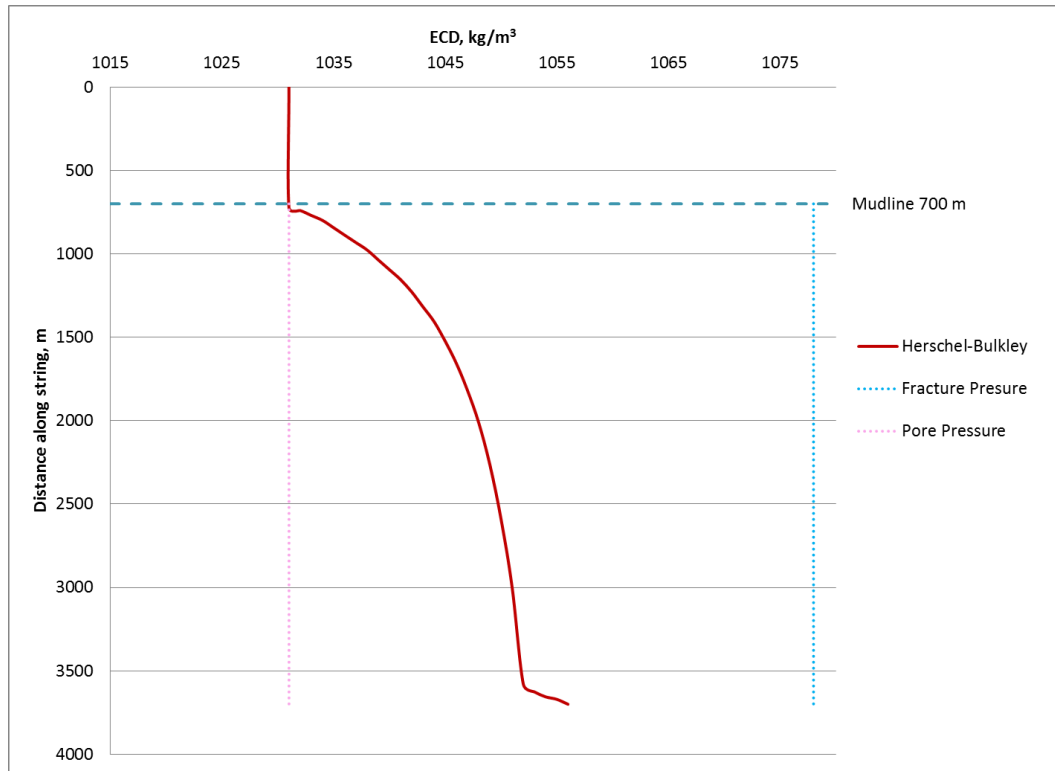


Fig. 4.5 – The ECD using gel sweeps show a greater increase in ECD than saltwater. The gradual increase of ECD with depth is larger for the sweeps than it is for saltwater, while the ECD increase across the BHA is lower in comparison.

The minimum flow rate required to prevent cutting bed buildup for the base case is with salt sweeps is shown in **Fig. 4.6**. The minimum flow rate required for the gel sweeps is almost the same as the minimum flow rate for saltwater. The flow rate required remains constant after the small decrease right below the seafloor until the BHA. The flow rate required decrease rapidly across the BHA.

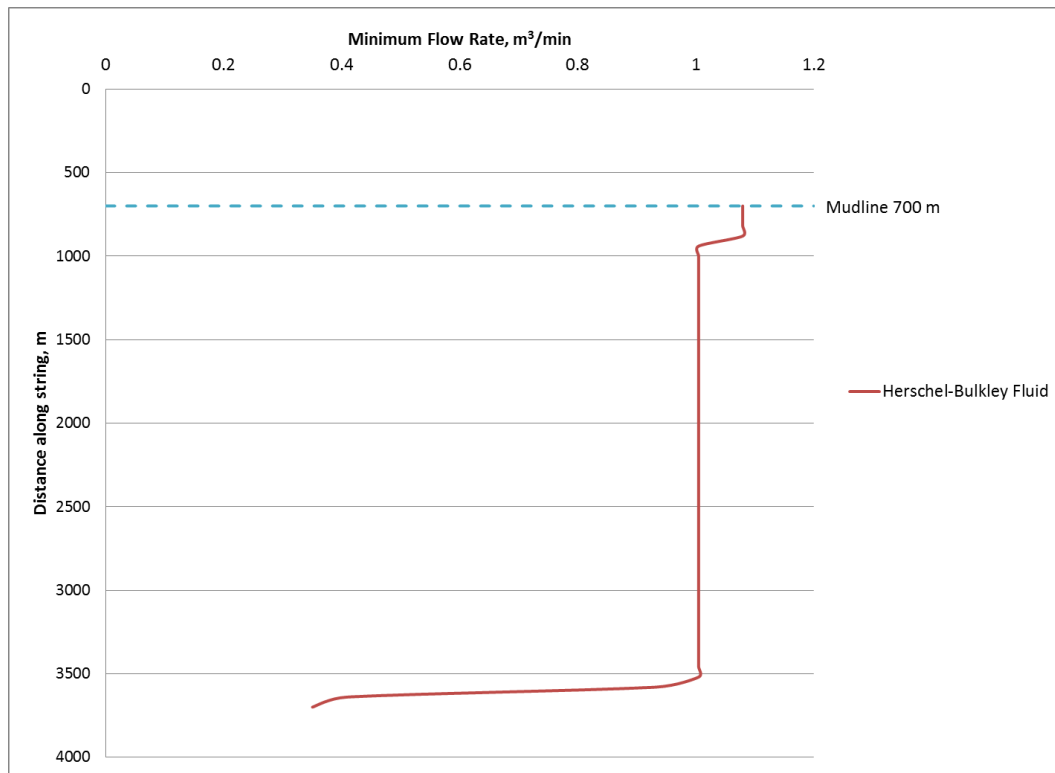


Fig. 4.6 – The minimum flow rate required to prevent cutting build up is almost the same for saltwater and gel sweeps. The flow rate slightly drops after the seafloor, and then remains constant until the BHA. At the BHA there is a significant decrease in the flow rate required to clean the annulus.

The volume suspended using gel sweeps only is displayed in **Fig. 4.7**. The gel sweep fluid suspend less than 0.1% cutting volume, indicating that a cutting bed will develop very slowly using the gel sweep.

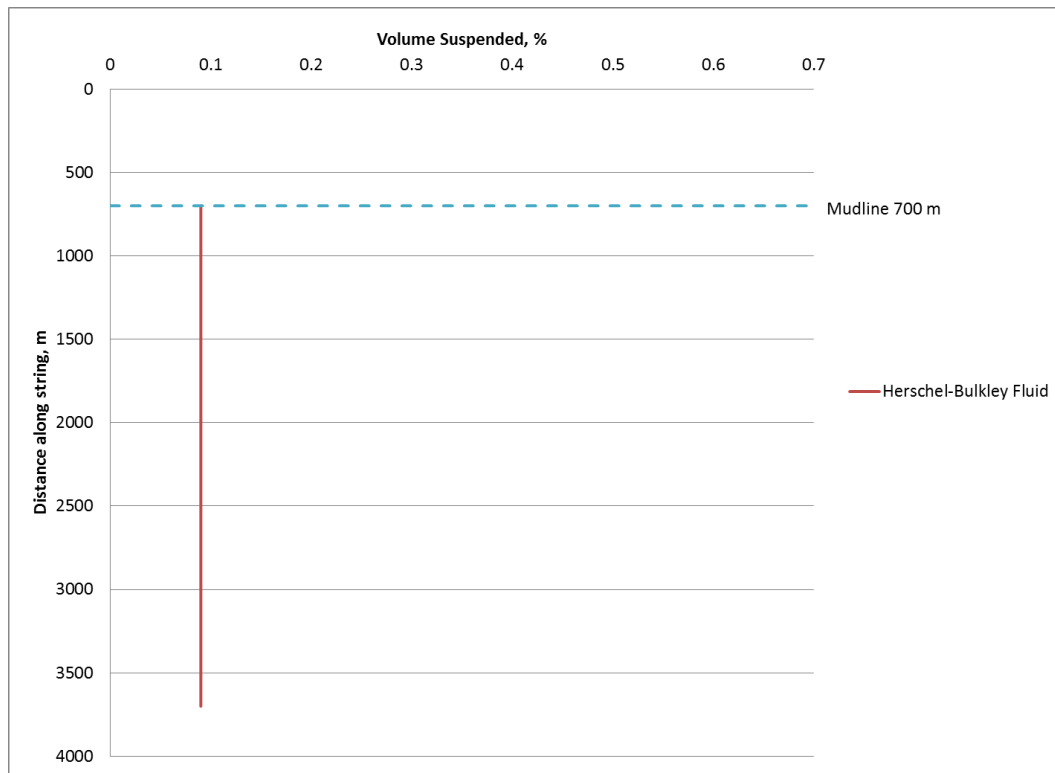


Fig. 4.7 – The gel sweeps have a constant volume suspended below 0.1% while circulating.

The geometry of the drill pipe affects the minimum flow rate required to clean the hole sufficiently at increasing depths. **Fig. 4.8** shows that when using 5 ½ inch drill pipe, the minimum flow rate is lower than when using 5 inch drill pipe for ROP's between 0 and 50 m/hr. Fig. 4.8 also show that past 50 m/hr, the flow rate required increase linearly, but is equal for 5 and 5 ½ inch sized drill pipe.

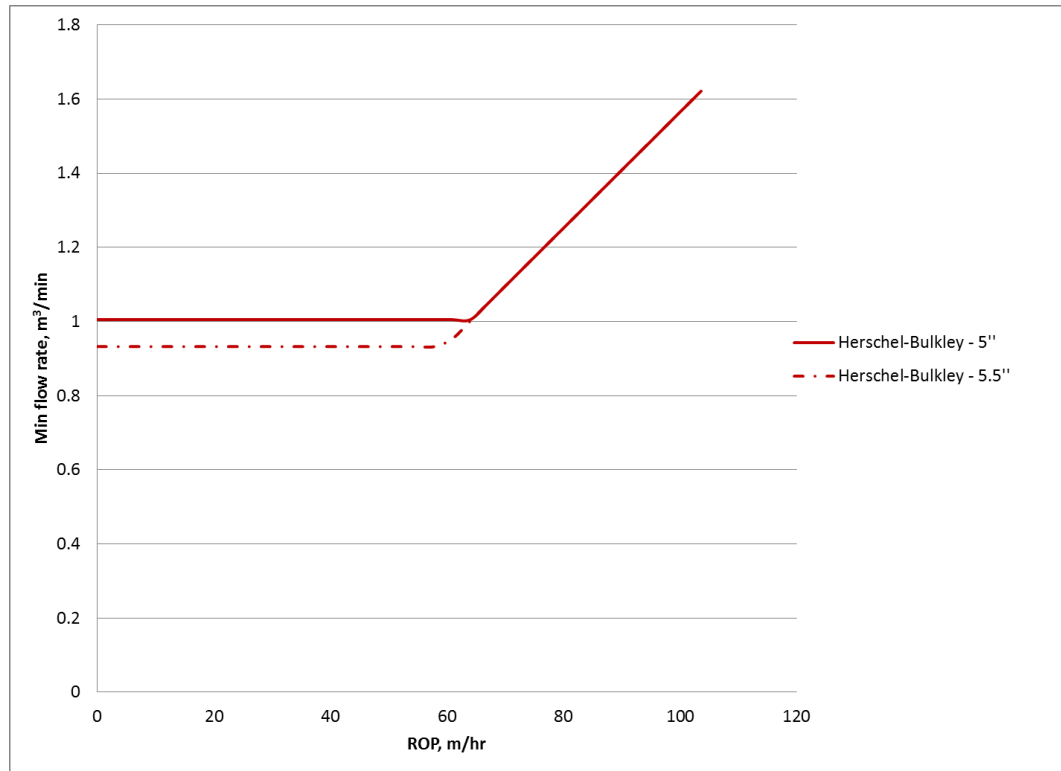


Fig. 4.8 – The minimum flow rate required to clean the hole remains constant for ROP's up to 50 m/hr, but then increase linearly. The 5" drill pipe require a higher flow rate for ROP's between 0 and 50 m/hr, but past 50 m/hr the flow rate for 5" and 5 ½" drill pipe remain the same using gel sweeps.

4.3. Sensitivity analysis

As the base parameters listed in Table 4.1 are estimates and averages, sensitivity analysis needs to be performed to ensure hole cleaning with varying parameters. For each of the parameters changed, the remaining parameters will be held constant.

4.3.1. Changing rate of penetration

When changing the rate of penetration (ROP), the remaining parameters will be held constant as shown in **Table 4.2**. For the ROP, the parameter values will be varied

from 1.5 m/hr to 5 m/hr. The change in ECD from the different ROP's can be seen in **Fig. 4.9**. Fig. 4.9 also shows that changing the ROP does not change the ECD for any given depth. The lines all overlay each other. The results for changing ROP at the depth of 875, 1750, and 2375 mbsf as well as the gel sweep results are displayed in **Appendix A**. The varied depths display similar trends, just higher, as the ECD in Fig. 4.9. The lower the depth, the faster the ECD increase, but the results all fall well within the operating window. For the gel sweeps, the trend displayed in Fig. 4.5 can be seen, but with a faster increase in ECD.

Table 4.2 – Parameter values held constant while changing ROP.

Variable	Value	Units
Pump Rate	2.348	m ³ /min
Cutting Density	3.00	SG
Cutting Diameter	5.00	mm

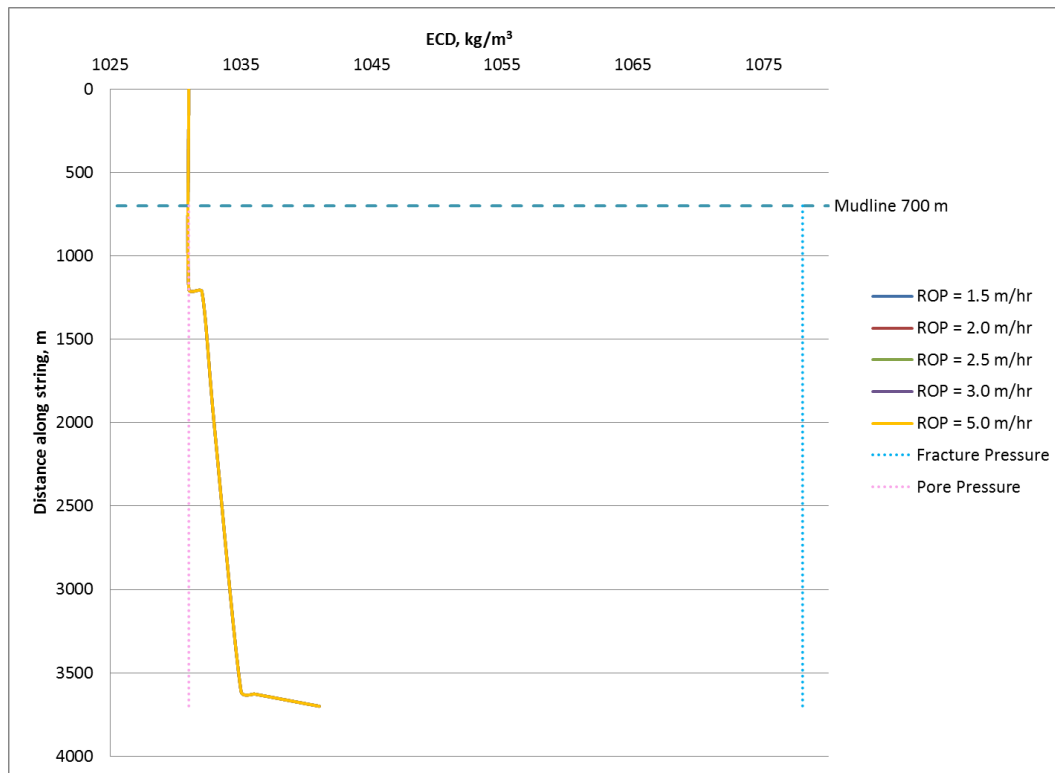


Fig. 4.9 – Changing ROP’s did not result in a change in ECD. The ECD does increase with increasing depth, but stay well within the operating window. The figure also shows a sharp increase in ECD over the BHA.

Fig. 4.10 shows that the flow rate required to prevent cutting build up does not change with changing ROP. All the lines fall on top of each other with a constant minimum flow rate required at the drill pipe and a sharp decrease required for cleaning the BHA. For the varied depths in Appendix A, the trend of Fig. 4.10 with the sharp decreased located the present depth of the BHA. The gel sweeps for the changing ROP’s also display similar trends as the saltwater with a slightly lower minimum flow rate for all depths.

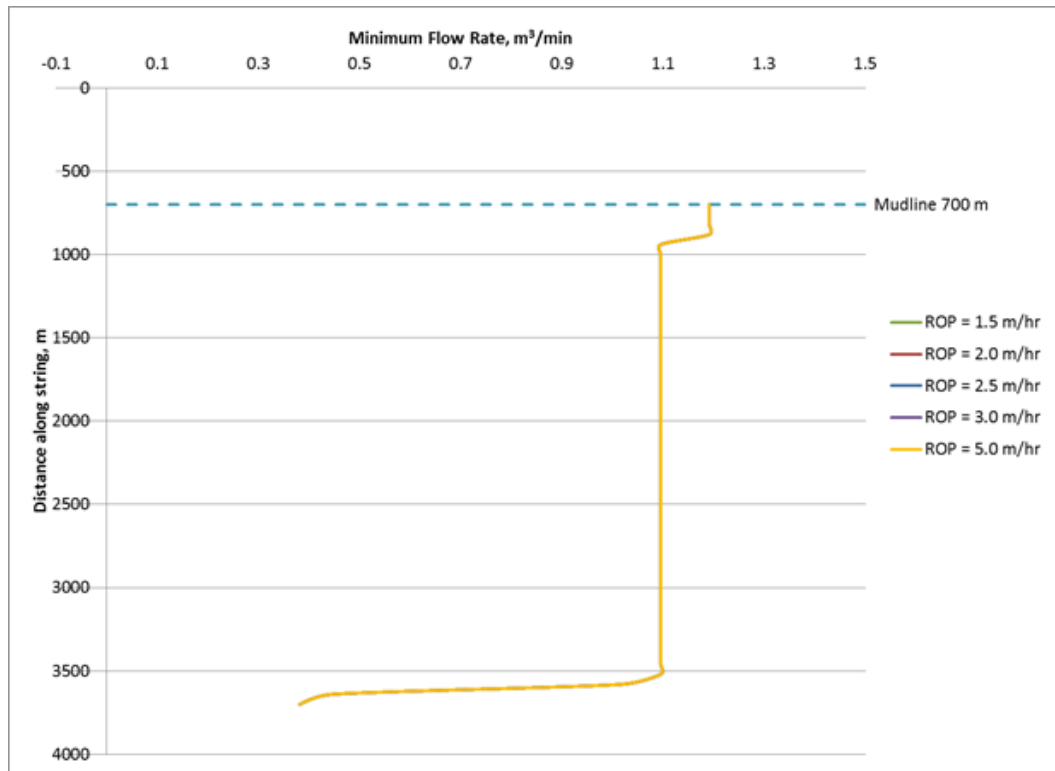


Fig. 4.10 – Changing ROP does not change the minimum flow rate required to prevent cutting concentration buildup. Following a decrease after the casing shoe, the flow rate remains constant for the majority of the time, with a sharp decrease over the BHA.

Fig. 4.11 shows that the volume of cuttings suspended will increase with increasing ROP's. When doubling the ROP from 2.5 m/hr to 5.0 m/hr, the volume suspended will approximately double from 0.13% to 0.26%. The volume suspended for previous modeled depths in Appendix A display similar results as Fig. 4.11. When applying gel sweeps, the cutting volume suspended decreases to approximately 0.09% for ROP of 2.5 m/hr and 0.18% for ROP's of 5 m/hr.

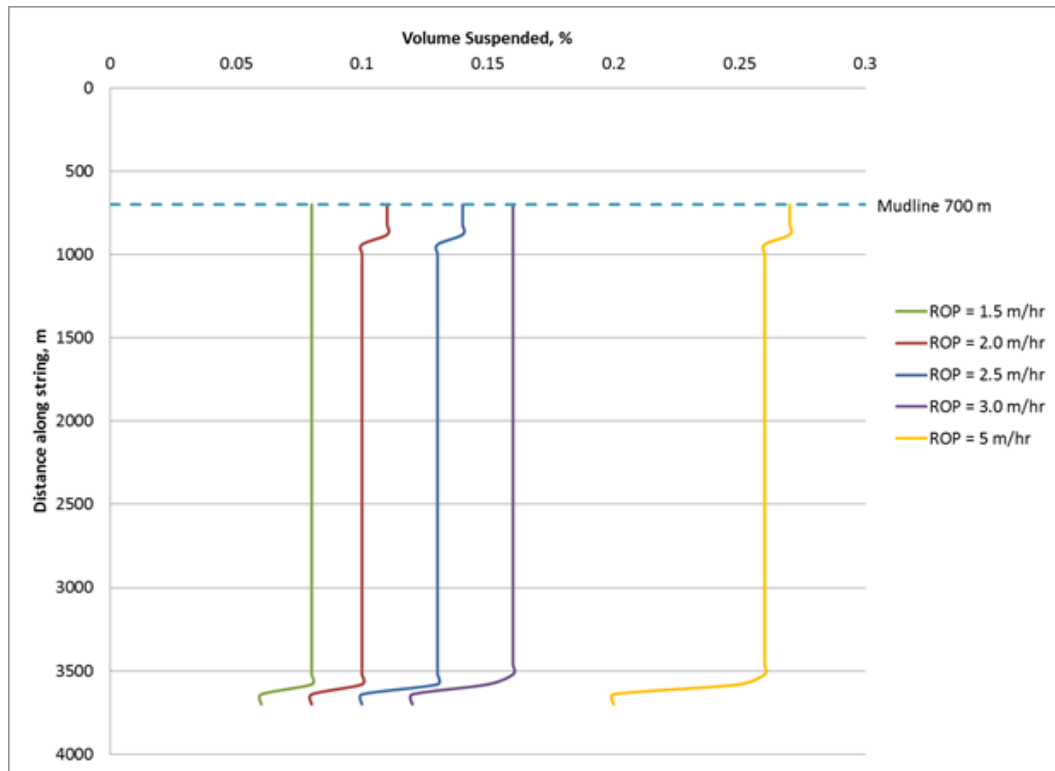


Fig. 4.11 – Increasing the ROP increases the amount of cutting percentage suspended in the annulus. With increasing ROP's, more cuttings will be created and the amount of cuttings that can be cleaned with constant parameters will decrease.

4.3.2. Changing pump rate

When changing the pump rate, the remaining parameters will be held constant as shown in **Table 4.3**. For the pump rate, the parameter values will be varied from 1 m³/min to 3 m³/min. The change in ECD from the different pump rates can be seen in **Fig. 4.12**. Fig. 4.12 also shows that changing the pump rates result in a change in the ECD for any given depth below the seafloor. Increasing pump rates increase the ECD along the drill string and the BHA. The results for changing pump rate at the depth of

875, 1750, and 2375 mbsf as well as the gel sweep results are displayed in **Appendix B**. Changing pump rates for the variables depths using seawater follow same trends as Fig. 4.12. The lower pump rates results in ECD less than the pore pressure for all depths using saltwater. Using saltwater, the pump pressures of 2.348 m³/min, the maximum pump rate when using one pump, and 3 m³/min stay within the operating window for all depths, while the lower pump rates fall below the pore pressure ECD. The gel sweeps stay well within the operating window for all pump rates at all depths.

Table 4.3 – Parameter values held constant while changing pump rate.

Variable	Value	Units
Rate of Penetration	2.5	m/hr
Cutting Density	3.00	SG
Cutting Diameter	5.00	mm

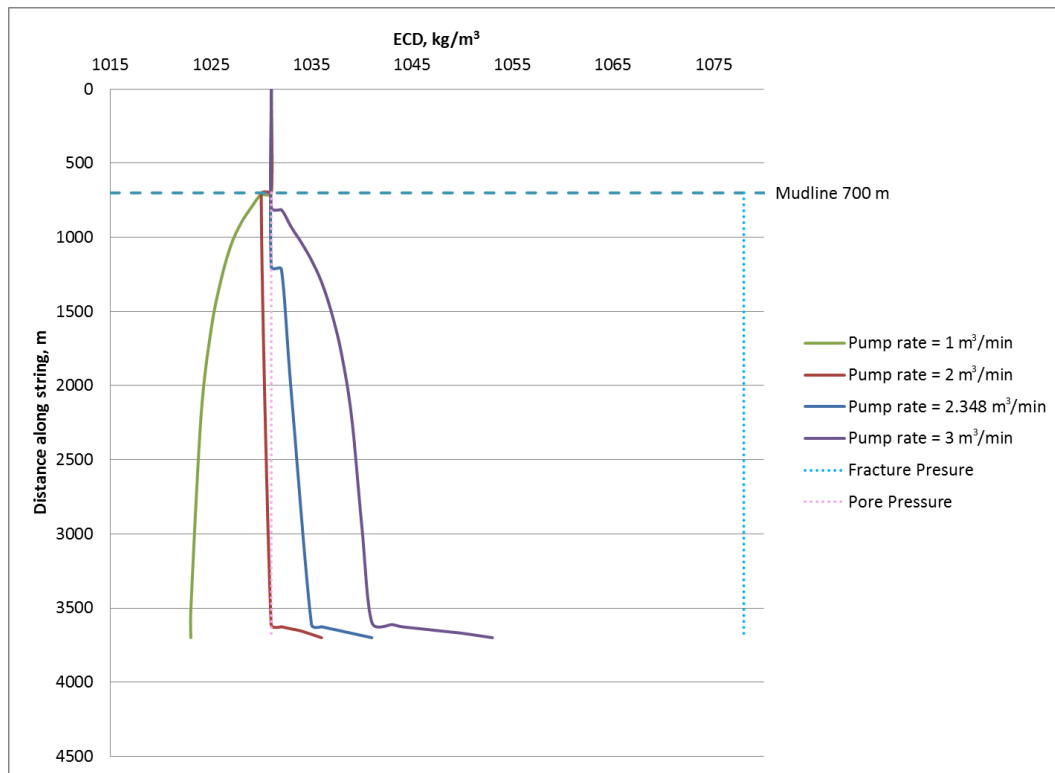


Fig. 4.12 – Increase in pump rate increases the ECD using saltwater at 3000 mbsf. With a pump rate of less than 2.348 m³/min, the ECD falls below the pore pressure which can result in an influx or kick. The increase in ECD is larger across the bit, but stays well within the operating window for 2.348 and 3 m³/min.

Fig. 4.13 shows that the flow rate required to prevent cutting build up does not change with changing pump rates. All the lines fall on top of each other with a constant minimum flow rate required at the drill pipe and a sharp decrease in flow rate required for cleaning the BHA. This minimum flow rate display the same trend for all depths using saltwater and gel sweeps. Gel sweeps maintain a slightly lower minimum flow rate than saltwater for all depths. The difference between the depths is shown by the time of sudden decrease across the BHA as the BHA is at a lower depth.

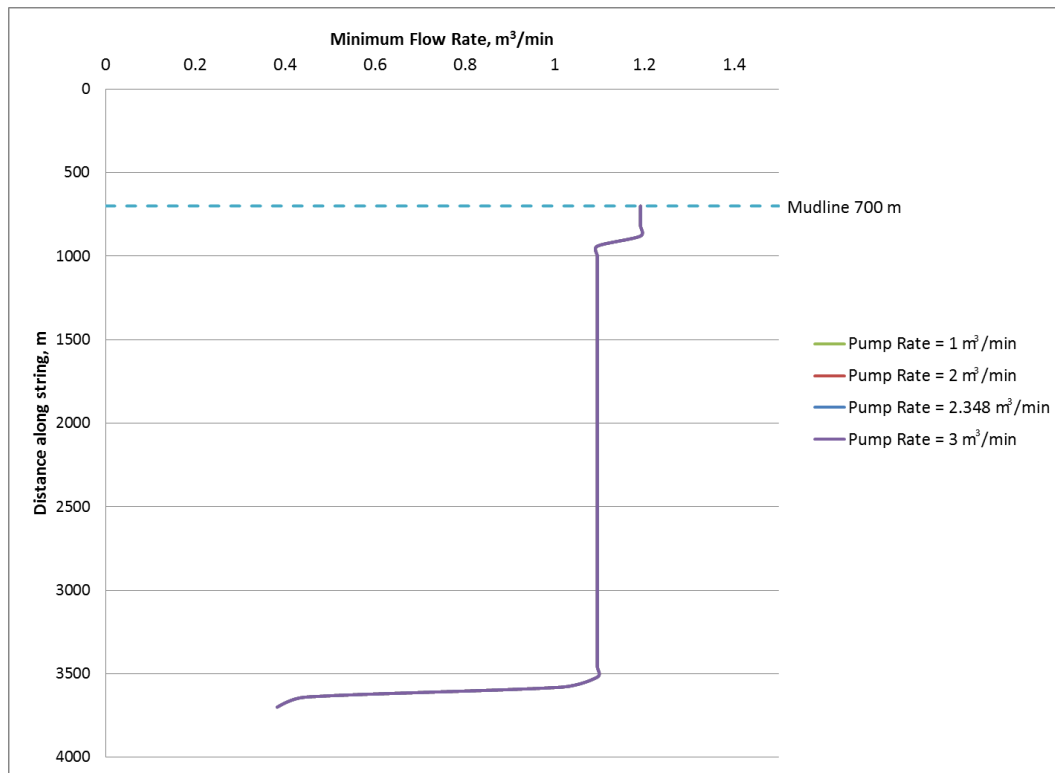


Fig. 4.13 – Changing pump rate does not change the minimum flow rate required to prevent cutting concentration for 3000 mbsf using saltwater. Following the decrease after the casing point, the flow rate remains constant for the majority of the time, with a sharp decrease across the BHA.

Fig. 4.14 shows that the volume of cuttings suspended will increase with decreasing pump rates. When decreasing the pump rate to from 2.348 m^3/min to 1 m^3/min , the volume of cuttings suspended increased from 0.15% to 0.7%. The different depths displayed in Appendix B follow the same trends for volume suspended using saltwater, but a lower volume for gel sweeps. When using gel sweep, the cutting suspended is increased from 0.09% to 0.21% for the pump rates of 2.348 m^3/min to 1

m^3/min . This is less than a third of the volume that was suspended using saltwater for the low pump rate of $1 \text{ m}^3/\text{min}$.

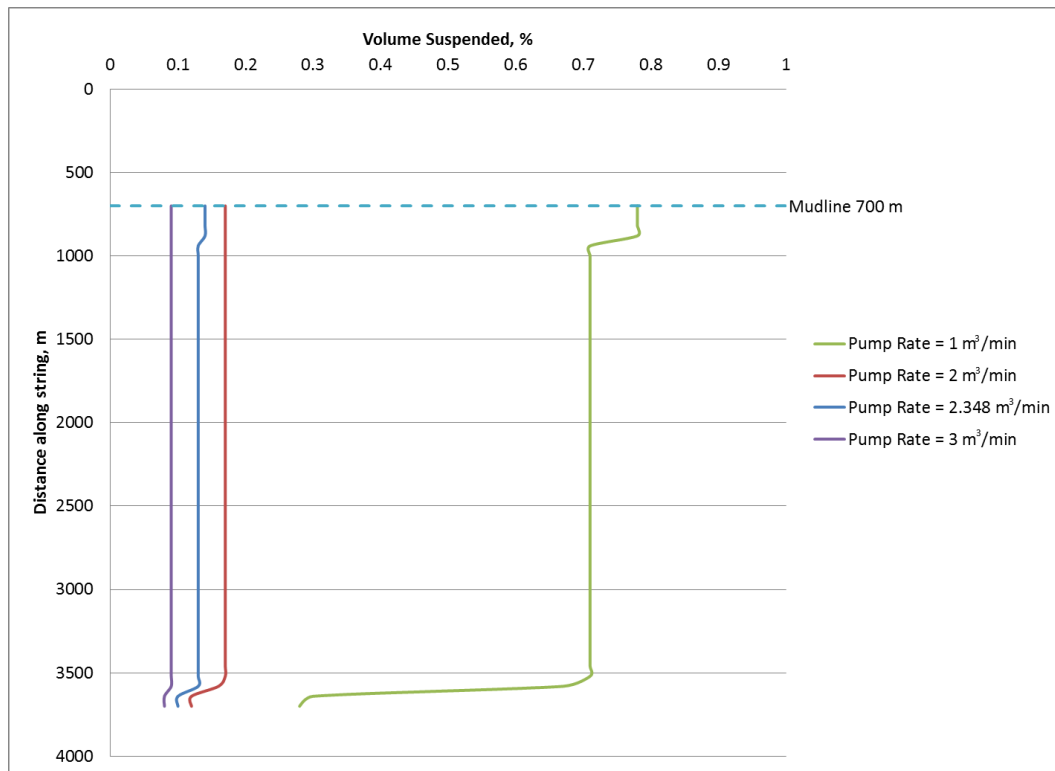


Fig. 4.14 – Decreasing the pump rate increases the amount of cutting percentage suspended in the annulus using saltwater at 3000 mbsf. With increasing pump rates, the annular velocity will increase, preventing cuttings from settling in the annulus. With a low pump pressure of $1 \text{ m}^3/\text{min}$, the cutting volume suspended is approximately 0.7%.

4.3.3. Changing cutting characteristics

The previous sections have discussed the parameters that a driller has some control over. The pump rate is decided by the driller while the ROP can be monitored

and adjusted with weight on bit (WOB). The following sections will discuss the unknown related to the cuttings created by the core bit. The density and the size of the cuttings are determined by the rock that is being penetrated. The size of the cuttings will remain an unknown as the cuttings are deposited on the seafloor. The density of the cuttings can be determined through the analysis of the core that is brought to the surface. However, both the diameter and density of the cuttings will vary at different intervals, so it is important to model different values to verify proper hole cleaning under varying conditions.

4.3.3.1. Density of cuttings

When changing the density of cuttings, the remaining parameters will be held constant as shown in **Table 4.4**. For the densities of the cuttings, the parameter values will be varied from a specific gravity of 1.5 to 3.5. The change in ECD from the different cutting densities can be seen in **Fig. 4.15**. Fig. 4.15 also shows that changing the cutting density does not change the ECD for any given depth. The lines all overlay each other. The results for changing cutting density at the depth of 875, 1750, and 2375 mbsf as well as the gel sweep results are displayed in **Appendix C**. The saltwater follows the trend in Fig. 4.15 for all depths, but with a faster increase in ECD. The gel sweeps follow the trend of the base case shown in Fig. 4.5, but increasing at a faster speed. The ECD stays within the operating window for all depths modeled using both saltwater and gel sweeps.

Table 4.4 – Parameter values held constant while changing cutting density.

Variable	Value	Units
Rate of Penetration	2.5	m/hr
Pump Rate	2.348	m ³ /min
Cutting Diameter	5	mm

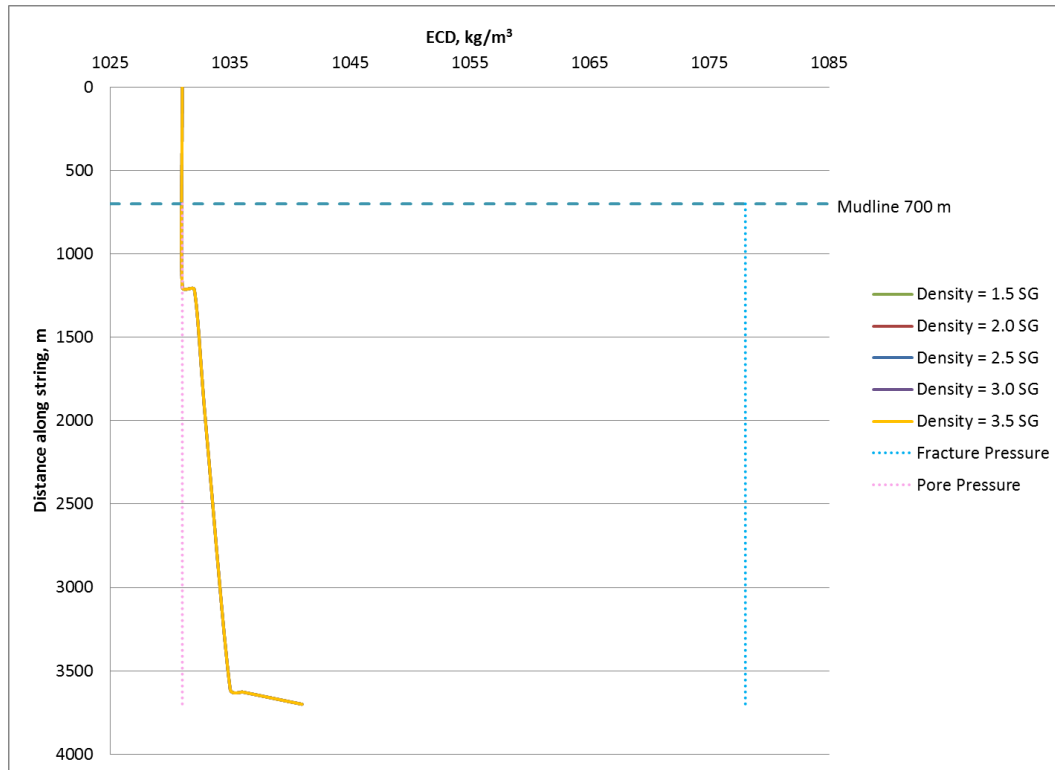


Fig. 4.15 – Changing cutting density did not result in a change in ECD using saltwater. The ECD does increase with increasing depth, but stay well within the operating window. The figure also shows a sharp increase in ECD over the BHA.

Fig. 4.16 shows that the flow rate required for preventing cutting buildup increases with increasing cutting density. However, the flow rate required to clean around the BHA is almost equal for all the modeled cutting densities. The minimum flow rate required for the depths displayed in Appendix C show the same results as Fig.

4.16, but with the BHA drop located at the present BHA location. The gel sweeps also display the same trend, but slightly lower, as the saltwater for the different depths.

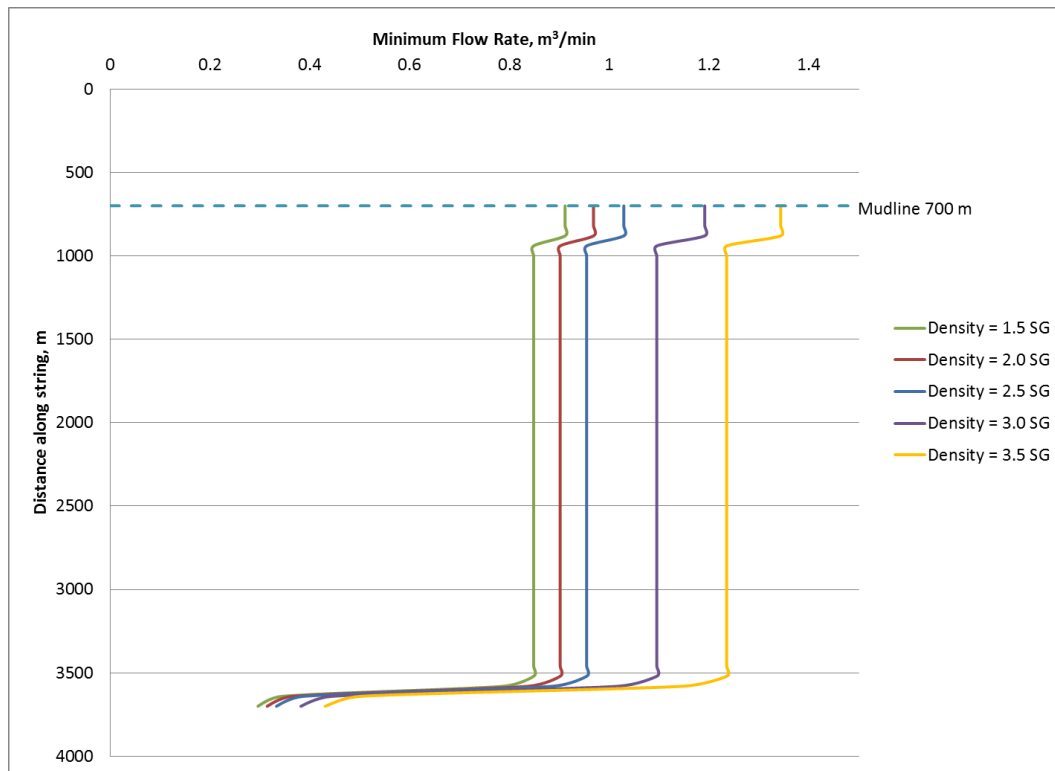


Fig. 4.16 – Increasing the cutting density increases the minimum flow rate required. The higher the specific gravity of the cutting density, the higher the flow rate required to prevent cutting concentration is. The flow rate required to clean the BHA remains nearly consistent for the different cutting densities.

Fig. 4.17 shows that the volume of cuttings suspended will increase with increasing cutting densities. The increase in cutting volume suspended only increase from 0.1% to 0.14% when increasing the density from 1.5 SG to 3.5 SG. The volume

suspended for the shorter depths modeled in Appendix C display similar trends as Fig. 4.17 with increasing volume suspended for each density. However, the gel sweeps has a constant volume suspended between the specific gravity of 1.5 and 3.5 of 0.09%.

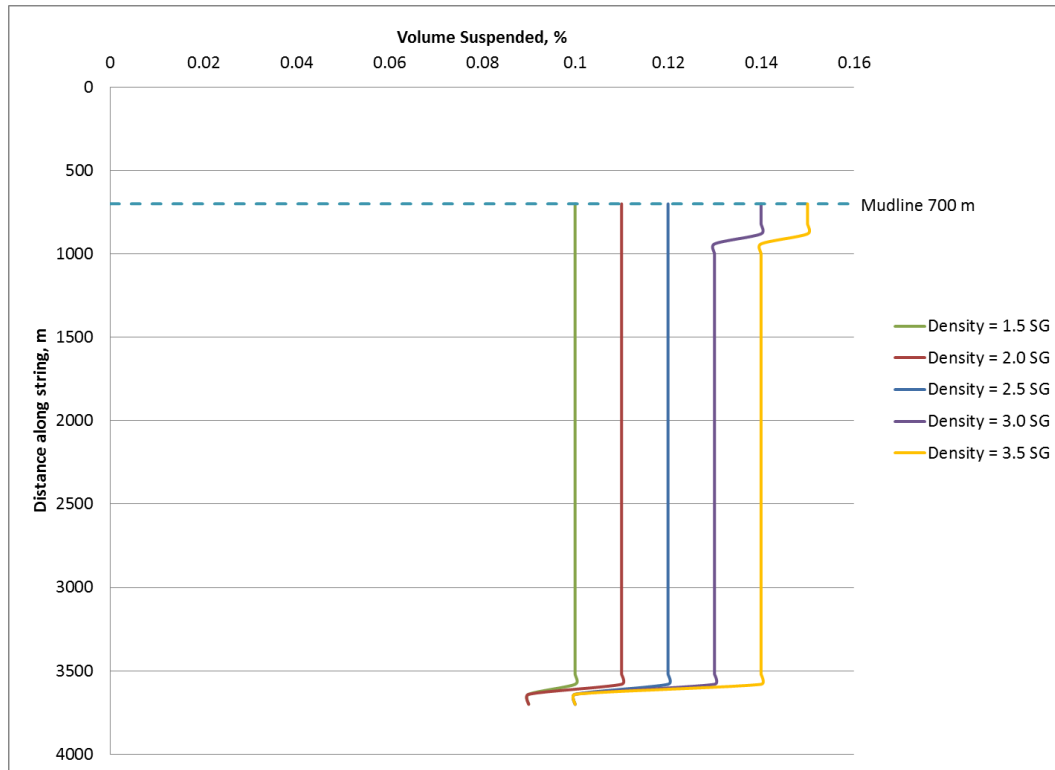


Fig. 4.17 –Increasing the cutting density increases the amount of cutting percentage suspended in the annulus. With increasing cutting densities, the particle velocity will increase which will suspend more cuttings in the annulus if the remaining variables are held constant.

4.3.3.2. *Size of cuttings*

When changing the size of cuttings, the remaining parameters will be held constant as shown in **Table 4.5**. For the size of the cuttings, the diameters will be varied

from 1 mm to 10 mm. The change in ECD from the different cutting sizes can be seen in **Fig. 4.18**. This figure also shows that changing the cutting size does not change the ECD for any given depth. The lines all overlay each other. The results for changing cutting size at the depth of 875, 1750, and 2375 mbsf as well as the gel sweep results are displayed in **Appendix D**. The saltwater follows the trend in Fig. 4.18 for all depths, but with a faster increase in ECD. The gel sweeps follow the trend of the base case shown in Fig. 4.5, but increasing at a faster speed. The ECD stays within the operating window for all depths modeled using both saltwater and gel sweeps.

Table 4.5 – Parameter values held constant while changing cutting diameter size.

Variable	Value	Units
Rate of Penetration	2.5	m/hr
Pump Rate	2.348	m ³ /min
Cutting Diameter	5.00	mm

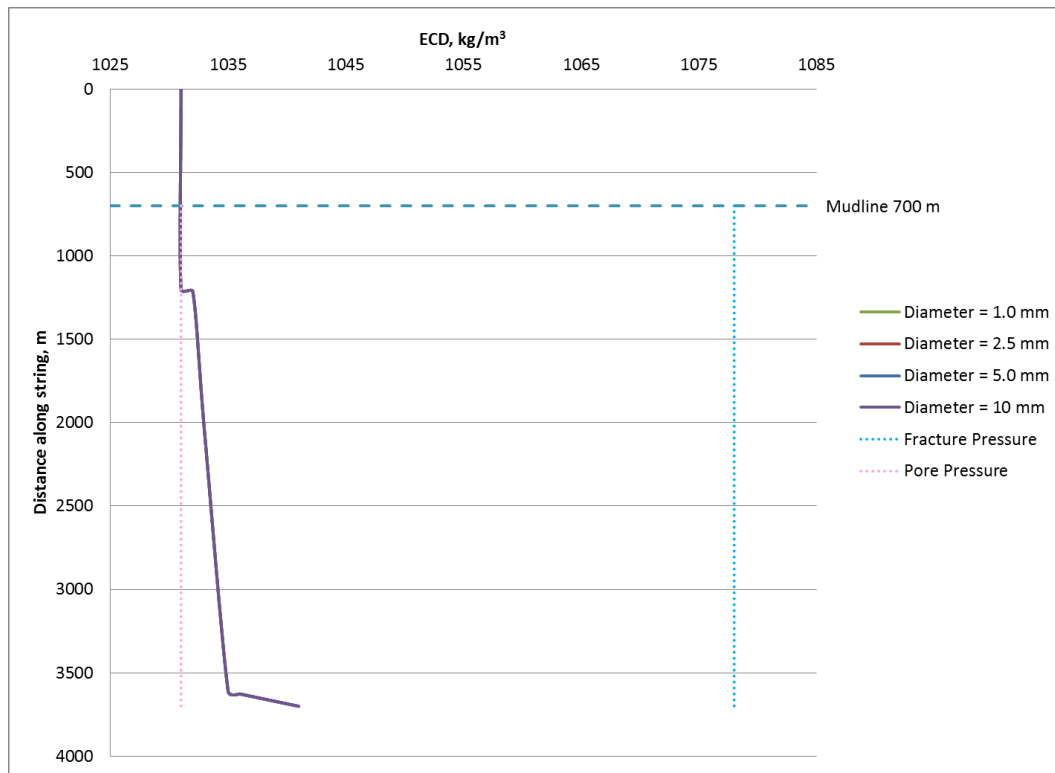


Fig. 4.18 – Changing cutting size did not result in a change in ECD for 3000 mbsf using saltwater. The ECD does increase with increasing depth, but stay well within the operating window. The figure also shows a sharp increase in ECD over the BHA.

Fig. 4.19 shows that the flow rate required to prevent cutting buildup remains constant for the small diameter cuttings of 1 – 2.5 mm. For 5 mm diameters, the minimum flow rate increases slightly. The minimum flow rate required for larger cutting diameter size of 10 mm requires twice the amount of flow rate as the small diameters require. This trend remains consistent for all the depth intervals seen in Appendix D using saltwater, while for the gel sweeps, the minimum flow rate does not change with

changing diameter. The flow rate remains constant at the lower flow rate required for all cutting diameter sizes.

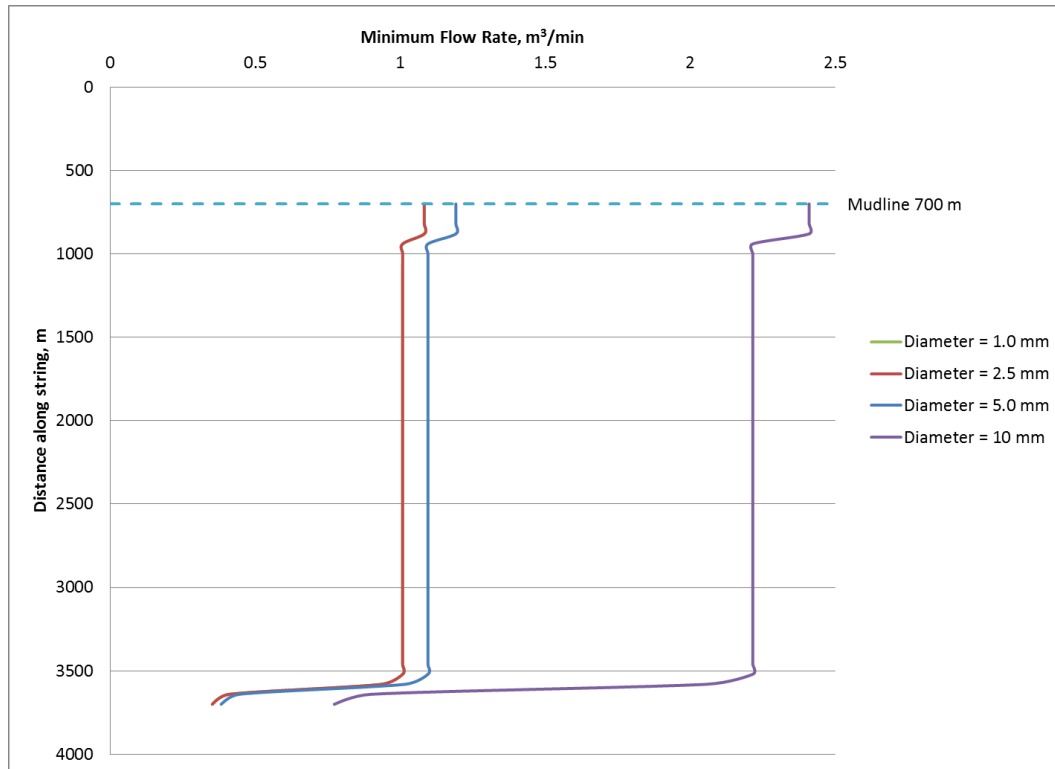


Fig. 4.19 – “Small” cutting diameter of 1-5 mm requires half the flow rate that the “large” cutting diameter of 10 mm requires to prevent cutting concentration buildup for saltwater at 3000 mbsf. The flow rate required to clean the BHA is smaller for both the smaller and larger cutting diameters.

Fig. 4.20 shows that the volume of cuttings suspended will increase with increasing cutting sized diameters. The increase in cutting volume suspended remains around 0.1% for the small cutting diameters, but increase to approximately 0.4% for the

larger cutting diameter of 10 mm. The volume suspended for the shorter depths modeled in Appendix D display similar trends as Fig. 4.20 with increasing volume suspended for each cutting size. However, the gel sweeps has a constant volume suspended for all diameters. The volume suspended for gel sweeps remains at a constant volume suspended of 0.09% versus the increase in saltwater that ends at 0.27% for 10 mm diameter sized cuttings.

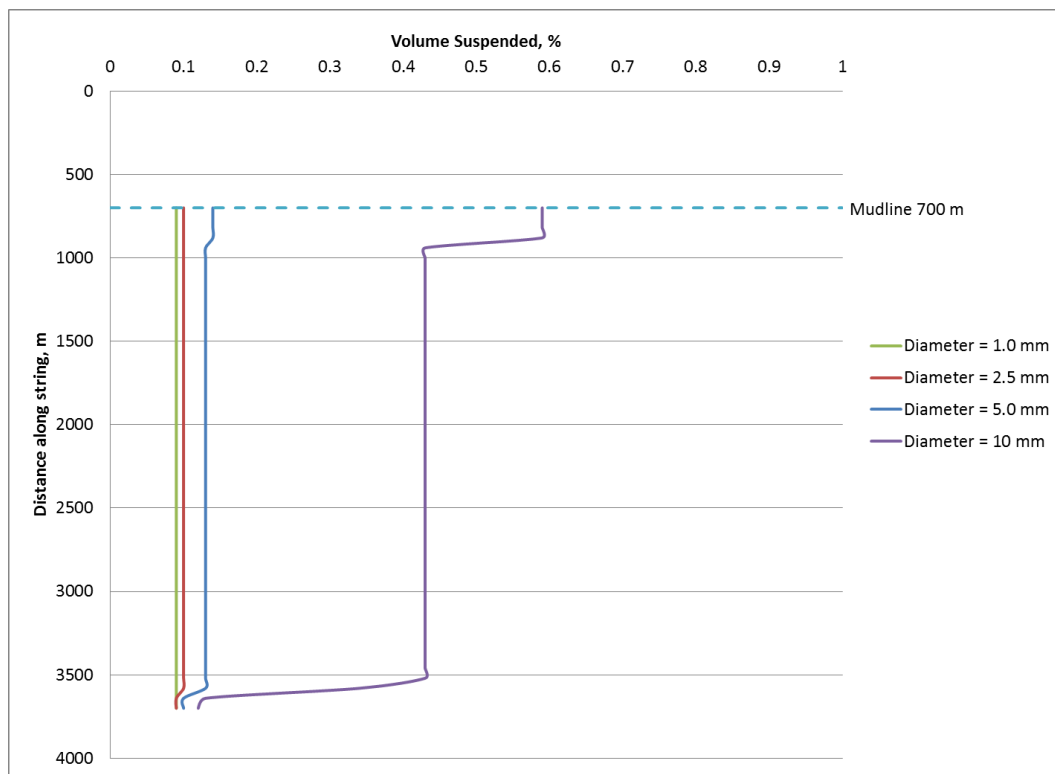


Fig. 4.20 – Increasing the cutting size increases the amount of cutting percentage suspended in the annulus when using seawater at 3000 mbsf. With increasing cutting size, the particle slip velocity will increase which will suspend more cuttings in the annulus if the remaining variables are held constant.

4.4. Efficient hole cleaning

From the displayed results, it is important to determine the efficiency of hole cleaning for different parameters. By setting a volume suspended value of 0.25% as being an accepted hole cleaning value, it can be determined if the hole is being properly cleaned at each of the given depths. Another parameter that needs to be considered for the hydraulics is to ensure the ECD falls within the operating window. For a given scenario to be efficient at proper hole cleaning, the volume suspended must therefore be less than 0.25% and the ECD must stay between the pore and fracture pressure.

Table 4.6 through Table 4.9 indicate whether the hole will be efficiently cleaned when changing parameters for the different depths. Most of the modeled scenarios passed the hole cleaning test, but a couple of the depths and parameters failed. For the saltwater drilling fluid the primary reason the tests failed was because of the volume suspended, while the gel sweeps failed because the fluid exerted by the drilling fluid exceeded the fracture pressure.

Table 4.6 – Indication if the change in ROP will efficiently clean the hole with a pump rate of 2.348 m³/min, cutting density with specific gravity of 3.0, and cutting diameter of 10 mm.

	Saltwater drilling fluid					Gel sweep fluids				
ROP, m/hr	1.5	2.0	2.5	3.0	5.0	1.5	2.0	2.5	3.0	5.0
675 mbsf	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes
1750 mbsf	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes
2375 mbsf	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes
3000 mbsf	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes

Table 4.7 – Indication if the change in pump rate will efficiently clean the hole with a rate of penetration of 2.5 m/h, cutting density with specific gravity of 3.0, and cutting diameter of 10 mm.

Pump Rate, m ³ /min	Saltwater drilling fluid				Gel sweep fluids			
	1.0	2.0	2.348	3.0	1.0	2.0	2.348	3.0
675 mbsf	No	No	Yes	Yes	Yes	Yes	Yes	Yes
1750 mbsf	No	No	Yes	Yes	Yes	Yes	Yes	Yes
2375 mbsf	No	No	Yes	Yes	Yes	Yes	Yes	Yes
3000 mbsf	No	No	Yes	Yes	Yes	Yes	Yes	Yes

Table 4.8 – Indication if the change in ROP will efficiently clean the hole with a rate of penetration of 2.5 m/hr, pump rate of 2.348 m³/min, and cutting diameter of 10 mm.

Cutting density, specific gravity	Saltwater drilling fluid					Gel sweep fluids				
	1.5	2.0	2.5	3.0	3.5	1.5	2.0	2.5	3.0	3.5
675 mbsf	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
1750 mbsf	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
2375 mbsf	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
3000 mbsf	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Table 4.9 – Indication if the change in ROP will efficiently clean the hole with a rate of penetration of 2.5 m/hr, pump rate of 2.348 m³/min, and cutting density with specific gravity of 3.0.

Cutting size, mm	Saltwater drilling fluid				Gel sweep fluids			
	1.0	2.5	5.0	10.0	1.5	2.5	5.0	10.0
675 mbsf	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes
1750 mbsf	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes
2375 mbsf	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes
3000 mbsf	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes

5. DISCUSSION

The JOIDES Resolution drill ship will be able to sufficiently clean the hole as long as parameters are carefully considered as seen in the sensitivity analysis. The difference in depths needs to be considered as some parameters will work for deeper depths but not in the shallower portion of the hole. It is important to ensure the pressure added from the fluid density remains within the operating window to avoid fluid loss or influx. The cutting volume suspended also has to be minimal for the hole to properly clean and allow for further penetration of the rock. The following sections provide guidelines that should be followed while drilling the hole.

5.1. Changing rate of penetration

The changing of rate of penetration (ROP) does not change the equivalent circulating density (ECD), so saltwater or gel sweeps can be used at any of the expected coring ROP's and still stay within the operating window. For the ROP, it is important to look at the volume of cuttings suspended as well. It can be seen in Fig. 4.11 that the increase in ROP results in an increase in volume suspended. To ensure proper hole cleaning at higher ROP's, gel sweeps should be added more often. As a general rule of thumb, the gel sweeps should be added every 30 m, or 100 ft (Lanthier 2014). When drilling at a faster ROP greater than 5 m/hr, the distance between the gel sweeps should be decreased to ensure the cutting volume suspended is as low as possible.

Fig. 4.11 and **Fig. A.24** shows that with an ROP of 5.0 m/hr, the cutting volume suspended is decreased from approximately 0.26% to 0.18% by using gel sweeps instead

of saltwater. This further verifies that the gel sweeps should be added to ensure that the cutting concentration develops slowly and allows for trouble-free drilling ahead.

5.2. Changing pump rate

The changing of pump rate does increase the ECD, so it is important to make sure that the resulting annular pressure remains within the operating window. With shallower depths, the higher pump rate has a greater potential affect than at deeper depths due to lower rock strength at these depths. The lower pump rates have a great effect on the ECD when using saltwater, which is shown when looking at all depths. With a pump rate less than 2.348 m³/min, the ECD falls below the pore pressure. Therefore, it is important to maintain a higher pump pressure. If only a lower pump rate is available, gel sweeps need to be added more frequently to increase the ECD and prevent influx from formations. It should still be noted that the pump rate needs to be lower for shallower depths due to rock strength concerns, while a higher pump rate is required for deeper depths to maintain annular velocity.

The volume suspended by using different pump pressures eliminates the use of 1 and 2 m³/min for saltwater-only fluids. The low pump rate of 1 m³/min generates approximately 0.7% cutting volume suspended, which result in the cutting concentration developing at a faster rate. If the cutting concentration is too high, the bit cannot penetrate new rock, which results in the bit grinding up the cuttings instead of generating more cuttings and increasing depth. If a low pump rate must be implemented, the gel sweeps should be added at shorter depth intervals as the cutting volume suspended is reduced from 0.7% to 0.21% for a pump rate of 1 m³/min.

5.3. Changing cutting characteristics

As the cutting characteristics are not controlled by the driller, it is important that the hole be cleaned properly with all the different parameters. The cutting density depends on the rock that is being drilled, and can vary when entering new formations. The cutting size is dependent on how efficient the bit is at grinding the rock. As both of these characteristics are unknowns, it is important to ensure the parameters can clean the hole properly at all times.

5.3.1. Changing cutting density

The expected rock to be encountered is gabbro, which is why the cutting density has been based on the typical densities for gabbro and basic igneous rocks. With the different parameters assigned for the base case, the hole can be properly cleaned for all gabbro. The ECD stays well within the operating window for both saltwater and gel sweeps. The cutting suspended has a small increase with each increasing density assigned, but still cleans the hole efficiently. The saltwater does clean the hole efficiently as the cutting volume suspended only reaches approximately 0.14%. The problem with the saltwater is the fact that it is a Newtonian fluid, so it does not have any gel strength. That means that as soon as circulation is stopped, the cuttings will settle at the bottom and generate a cutting bed. It is therefore important to add the gel sweeps with regular intervals, as they have the characteristics of a Herschel-Bulkley fluid. This means that the added gel strength from the gel sweeps can suspend the cuttings under static and circulating conditions. The gel sweeps also decrease the volume of cuttings suspended, which increase hole cleaning efficiency.

5.3.2. *Changing cutting size*

The average cutting size determined by WELLPLAN™ is given as 2.54 to 6.35 mm. This means that the cutting size can be smaller or larger depending on the rock and the bit characteristics. If there is enlargement of the hole, the cutting diameter will be even greater. The modeling of cleaning the different sizes of cuttings from the wellbore must therefore be accounted for. The ECD remains constant for the different cutting sizes, and falls well within the operating window for both the saltwater and the gel sweeps.

It should be noted that the minimum flow rate required for preventing cutting concentration from developing doubles for the larger diameter of 10 mm. The smaller diameters of 1 – 5 mm have approximately the same minimum flow rate required, while the 10 mm cutting size almost doubles the requirements. This is because the larger diameter cuttings need a much higher flow rate to clean the hole as can be seen in the volume suspended. The volume suspended for 10 mm sized cuttings is more than three times the amount than the smaller diameters. The volume for cutting size of 5 mm is approximately 0.13% while the cutting size for 10 mm is 0.43%. The larger cuttings require more gel sweeps and higher flow rates to clean the hole. When using gel sweeps instead of saltwater, the cutting suspended reduces to 0.09% for the 10 mm sized cuttings. The hole will therefore be sufficiently cleaned for diameters of 1 – 10 mm as long as gel sweeps are added regularly.

5.4. Changing drill pipe size

The increase of the drill pipe size reduces the minimum flow rate required for the different ROP's. As can be noted in Fig. 4.4, the larger diameter of 5 ½ inch drill pipe reduces the minimum flow rate required to clean the hole. As the geometry of the drill string remains constant while changing parameters, the minimum flow rate will not change when changing parameters as can be seen in Appendix A – D. The graphs comparing minimum flow rates to ROP do not change based on depth or parameters. The only difference in minimum flow rate is experienced when changing from saltwater to gel sweeps. The gel sweeps maintains a constant minimum flow rate up to 60 m/hr, while the saltwater starts a linear increase at 20 m/hr. The other difference is that past 60 m/hr, the gel sweep requires the same flow rate for 5 ½ and 5 inch drill pipe, while the saltwater always requires a lower flow rate for 5 ½ inch drill pipe. Therefore, when designing the drill string, the 5 ½ inch drill pipe should be used when only a lower pump rate is available.

5.5. Drill ship fluid storage capacity

To determine if the drill ship has the capacity to store the fluids required to drill to the moho, the total volume of gel sweeps needs to be determined. As a general rule of thumb, gel sweeps should be added every 30 m, or 100 ft (Lanthier 2014). For a 3000 m well, that results in one hundred gel sweeps required for the entire well. Using an average of 20 bbl sweep, the resulting total gel sweep fluid required is 2000 bbl. The JR drill ship has a capacity to hold 3714 bbl of fluid at the ship, so the 2000 bbl can mixed beforehand or continuously as the gel sweeps are required. If all the gel sweep fluid is

mixed before the expedition, approximately 1714 bbl will be available to continuously refill with saltwater while drilling. Therefore, the JR drill ship should have the fluid storage capacity required to drill to the moho as long as saltwater can continuously be pumped from the ocean to the pump pits.

5.6. Limitations with WELLPLANTM

WELLPLANTM was used for the modeling discussed, but it should be noted that there are several limitations with using this program for sensitivity analysis. The first limitation is that WELLPLANTM only allows the use of one drilling fluid at a time. That means that gel sweeps could not be added at different intervals or simulated as discrete volumes going up the annulus. The sensitivity analysis had to be generated using two separate simulations using saltwater and gel mud. Therefore WELLPLAN could not correctly display how gel sweeps and water interface and mix at that interface and how the combination cleaned the well. However, prior portions of this report have shown that saltwater is a very capable drilling fluid in most of the situations investigated. Thus, it can be assumed that given the excellent results from a gel mud system coupled with the adequate results from straight saltwater, the use of sweeps on a regular basis will result in a the lower cost, reduced pump pressures and reduced storage needs gained with saltwater and the extra hole cleaning capability due to the gel sweeps.

Another limitation with using a program like WELLPLANTM is that hole enlargement is not considered. To simulate the enlargement of a hole, a separate analysis needs to be run to determine how efficient the hole cleaning will be. With enlargement of hole, parameters that will greatly affect the hole cleaning are the increase in hole size

as well as the expected increase in cutting diameter size. **Fig. 5.1** shows the results from WELLPLAN™ by increasing the size and the cutting diameters.

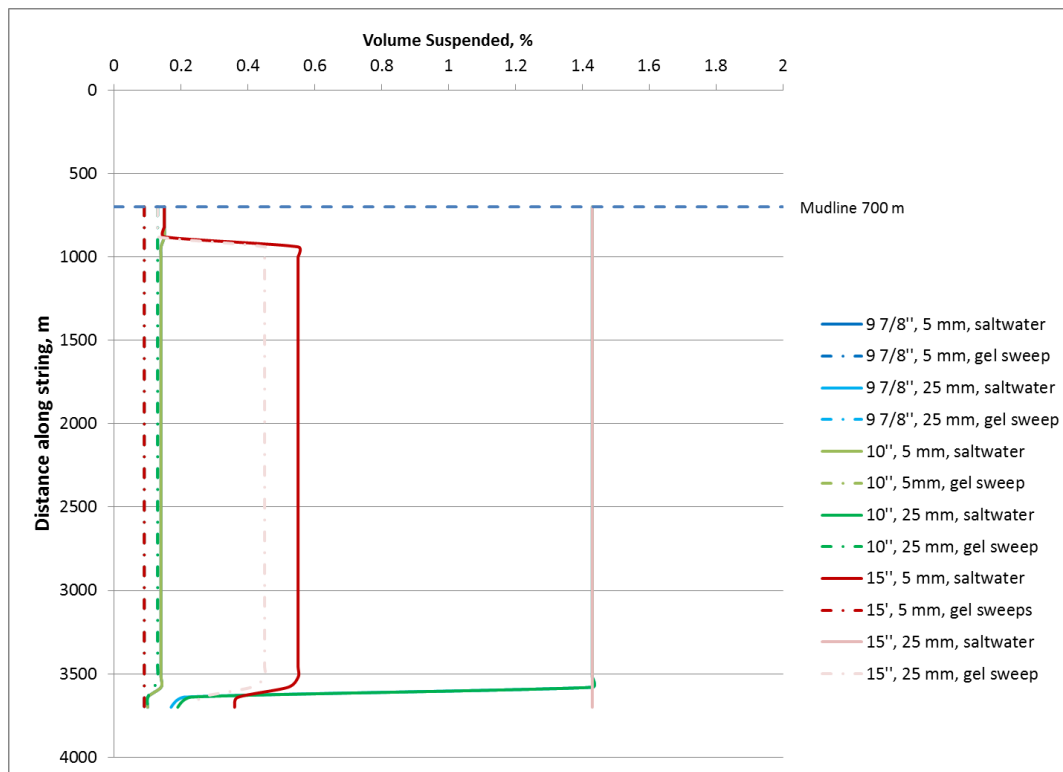


Fig. 5.1 – The effect of cutting volume suspended with hole diameters ranging from 9 7/8 in to 15 in as well as cutting diameter sized 5 mm and 25 mm. The first number indicate the hole size, second is diameter size, and finally what drilling fluid is used. Enlarged hole will prevent the hole from being cleaned properly with saltwater.

Fig. 5.1 shows that with 9 7/8 in hole, the volume suspended stays below 0.2% for saltwater and 0.09% for gel sweeps with 5 mm diameter size. By increasing the diameter size to 25 mm, the gel sweep increases to 0.13% and saltwater to 1.43%. This

means that with saltwater, the hole will not be cleaned properly if the cutting sizes increase to 25 mm, which is an indication of borehole instability with increasing hole size. With a cutting volume suspended being above 1%, it indicates that the cutting concentration is very high at the bit which can generate problems in drilling ahead.

It can be seen in Fig. 5.1 that the increase in hole size to 10 in does not have an increase in cutting volume suspended for any of the parameters. However, when the hole is enlarged to 15 in, there is a significant increase in cutting volume suspended. With 5 mm diameter cutting sizes, the volume suspended for saltwater increases to 0.6%, which is very poor hole cleaning. This shows that if there is hole enlargement with small cutting diameters, the cutting concentration might still allow drilling ahead, while if the cutting size gets to 25 mm, the cutting buildup will most likely prevent further drilling progress.

6. CONCLUSIONS AND RECOMMENDATIONS

Based on modeling and sensitivity analysis, it can be concluded that the JOIDES Resolution should not experience issues related to drilling fluid storage, hole cleaning or hydraulics when drilling to the moho or upper mantle. Careful consideration should be taken when deciding what parameters can be used in order to achieve proper hole cleaning.

Several conclusions and recommendations from this study include:

- 15-20 bbl gel sweeps should be added every 30 meters to achieve proper hole cleaning when drilling with saltwater.
- With higher ROP's, gel sweeps should be added more frequently to avoid cutting concentration buildup.
- Lower pump pressures will fall below the pore pressure and could result in kicks, or influxes. However, with the expected rock being gabbro with very low permeability, the low pump pressure is considered to be more of a stability issue, and therefore going slightly below pore pressure can be acceptable.
- Very low pump pressures will result in high volumes of cuttings suspended when using saltwater. If very low pump pressures must be used due to surface equipment pressure limitations, gel sweeps should be added at shorter intervals.

- The cutting density does not increase the cutting volume suspended by much, so with the rock expected, proper hole cleaning should be expected with the planned saltwater base fluid and gel sweeps.
- It is important to ensure the hole is cleaned properly if wellbore instability is present. One way to prevent this is to increase the mud weight to prevent hole enlargement from wellbore instability.

Based on the sensitivity analysis, it is recommended that the different parameters studied be monitored during the drilling process. The gel sweeps must be created to hold a yield point between 20 and 25 for suspension of cutting when static, and not circulating. With higher ROP's or lower pump rates, gel sweeps should be added more frequently.

7. RECOMMENDED FUTURE RESEARCH

Future research on the topic should include improvement in program used for simulation of different models. A program that can simulate the addition of gel sweeps to drilling fluid should be implemented for more thorough research on the topic. Improving sweep modeling in a program can show how the column of mud is affected based on the discrete volumes of very different drilling fluid that will be used for sweeps. By analyzing how the combinations of base drilling fluid and sweeps flow through the drill pipe and annulus, a better representation of the cutting volume suspended and hole cleaning efficiency can be found. Once the ability to simulate sweeps has been achieved, the program should be further improved to model the interface between the different fluids. Adding a gel sweep will create a mixture zone with the gel sweep and saltwater which should be simulated for the suspension capacity of the interface zone.

Another topic for further research would be to collect and use more extensive data for the simulation. By collecting more data from offset wells or other sources, it would improve the simulation's accuracy. The density of the rock being drilled could be found based on core samples. The permeability of the formation could be determined using logging tools to determine how far below the pore pressure the equivalent circulating density can fall. Fracture pressure could also be determined from leak-off tests or compressive strength of the rocks. The diameter size of the cuttings could be monitored by using a camera at the seafloor. Knowing more data would improve the

simulations and make the modeling more specific for the given drilling area instead of using data based on general information of the rocks around the world.

NOMENCLATURE

a	= Constant coefficient of 16
b	= Constant coefficient of 1
D_H	= Inside diameter of casing or the hole, inch
D_P	= Outside diameter of pipe, inch
D_{tvd}	= True vertical depth, ft
ECD	= Equivalent circulating density, ppg
EMW	= Equivalent mud weight, ppg
F_T	= Fluid transport ratio, dimensionless
g	= Gravitational coefficient
K	= Fluid consistency index, Pa•s ⁿ
$mbsf$	= meters below sea floor, m
n	= Flow behavior index, dimensionless
P	= Pressure, psi
P_h	= Hydrostatic pressure change to ECD point, psi
P_f	= Frictional pressure change to ECD point, psi
Q	= Flow rate, gpm
Q_{gb}	= Dimensionless flow rate
Q_{crit}	= Critical flow rate for bed to develop, m ³ /m
r_h	= Radius of wellbore or casing, mm
r_p	= Radius of drillpipe, mm
SG	= Specific Gravity, dimensionless

V_a = Annular velocity, ft/min

V_{slip} = Slip velocity of cutting particles, ft/min

W_{mud} = Fluid weight, ppg

ΔD_{md} = Measured depth annulus section length, ft

$\frac{\Delta P}{\Delta L}$ = Change in pressure per length along the annulus section, psi/ft

θ_3 = Mud viscometer reading at 3 RPM

θ_6 = Mud viscometer reading at 6 RPM

θ_{300} = Mud viscometer reading at 300 RPM

θ_{600} = Mud viscometer reading at 600 RPM

ρ = Fluid density, kg/m³

τ_y = Yield stress, Pa

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APPENDIX A

RESULTS FOR CHANGING ROP

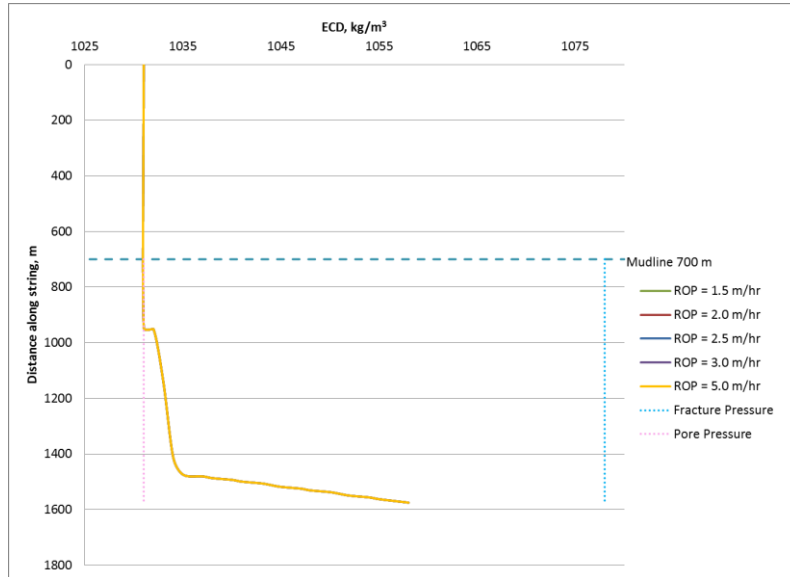


Fig. A.1 – Changing ROP's did not result in a change in ECD for 875 mbsf using saltwater. The ECD does increase with increasing depth, but stay well within the operating window. The figure also shows a sharp increase in ECD over the BHA.

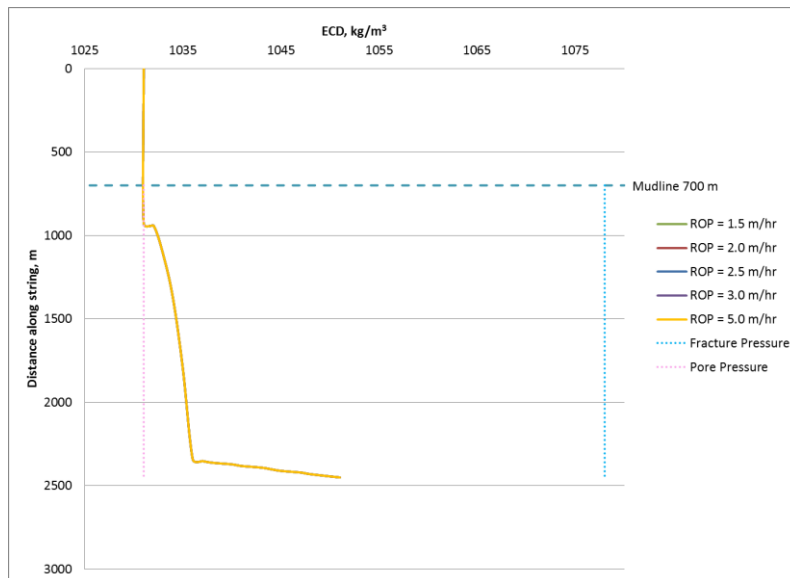


Fig. A.2 – Changing ROP's did not result in a change in ECD for 1750 mbsf using saltwater. The ECD does increase with increasing depth, but stay well within the operating window. The figure also shows a sharp increase in ECD over the BHA.

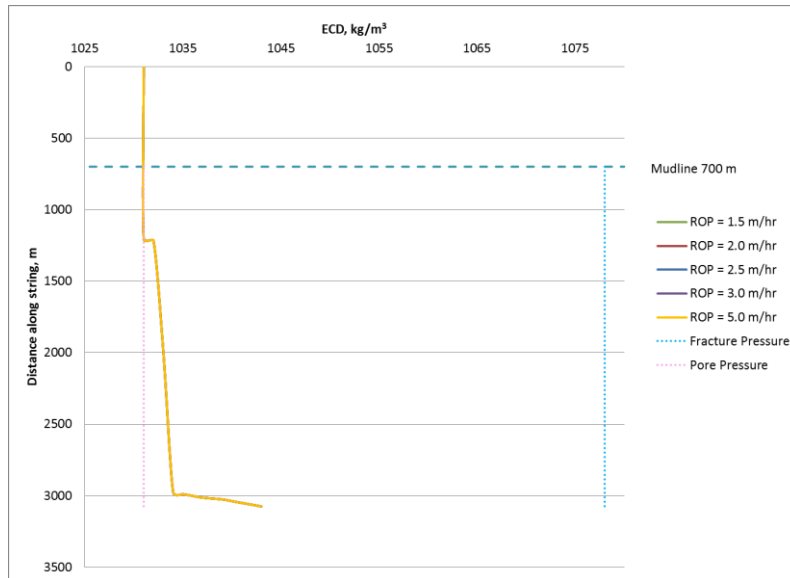


Fig. A.3 – Changing ROP’s did not result in a change in ECD for 2375 mbsf using saltwater. The ECD does increase with increasing depth, but stay well within the operating window. The figure also shows a sharp increase in ECD over the BHA.

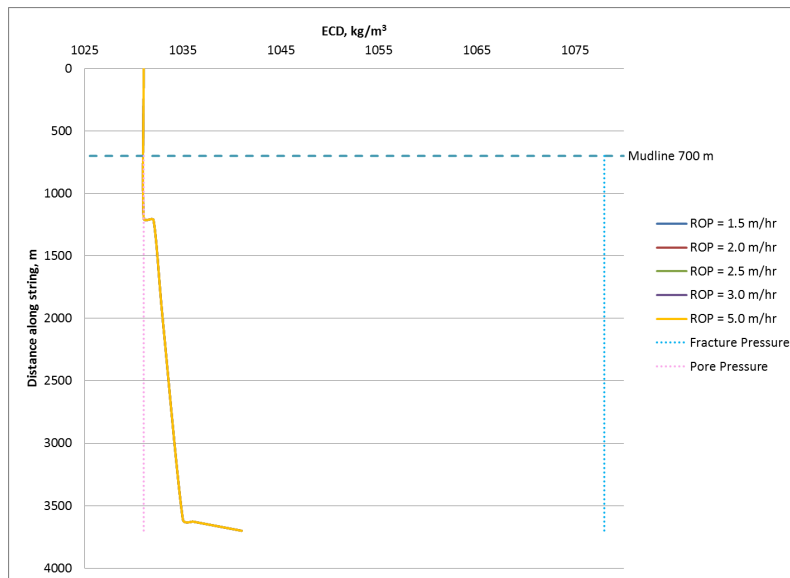


Fig. A.4 – Changing ROP’s did not result in a change in ECD for 3000 mbsf using saltwater. The ECD does increase with increasing depth, but stay well within the operating window. The figure also shows a sharp increase in ECD over the BHA.

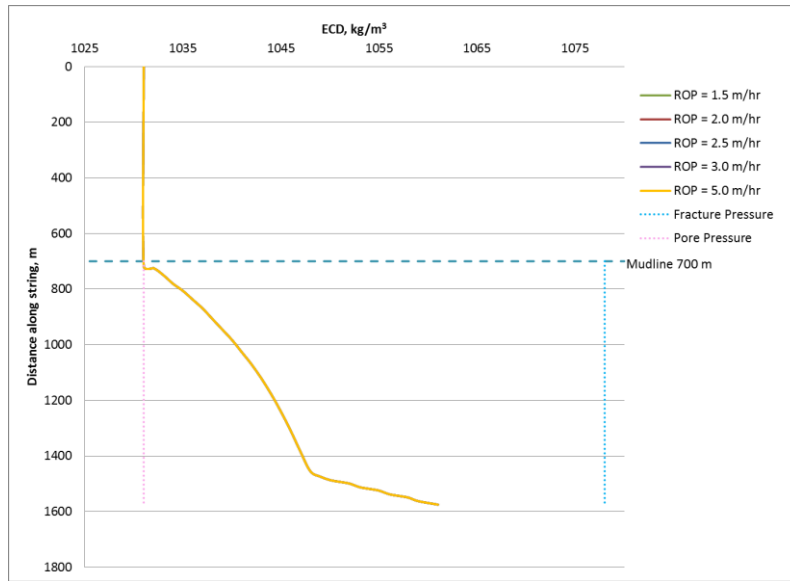


Fig. A.5 – Changing ROP did not result in a change in ECD for 875 mbsf using gel sweeps. The ECD does increase faster using gel sweeps than saltwater, but stays well within the operating window. The increase in ECD across the bit can also be seen using gel sweeps.

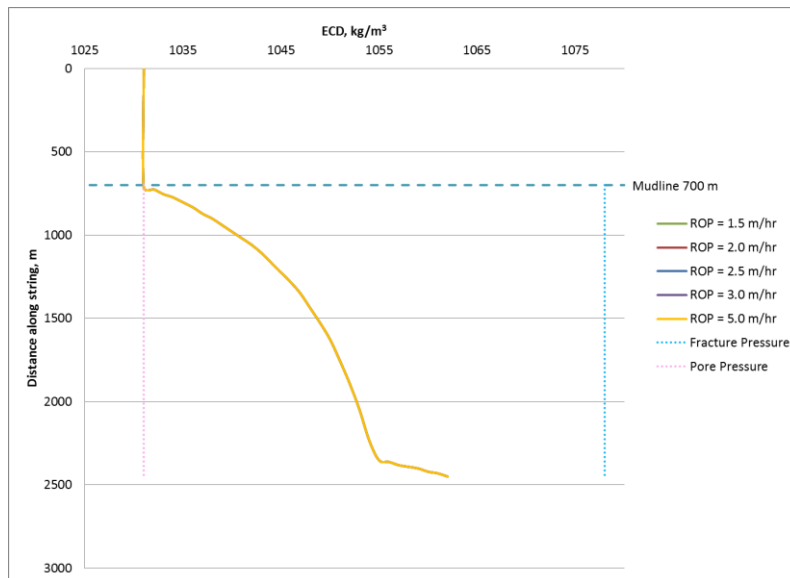


Fig. A.6 - Changing ROP did not result in a change in ECD for 1750 mbsf using gel sweeps. The ECD does increase faster using gel sweeps than saltwater, but stays well within the operating window. The increase in ECD across the bit can also be seen using gel sweeps.

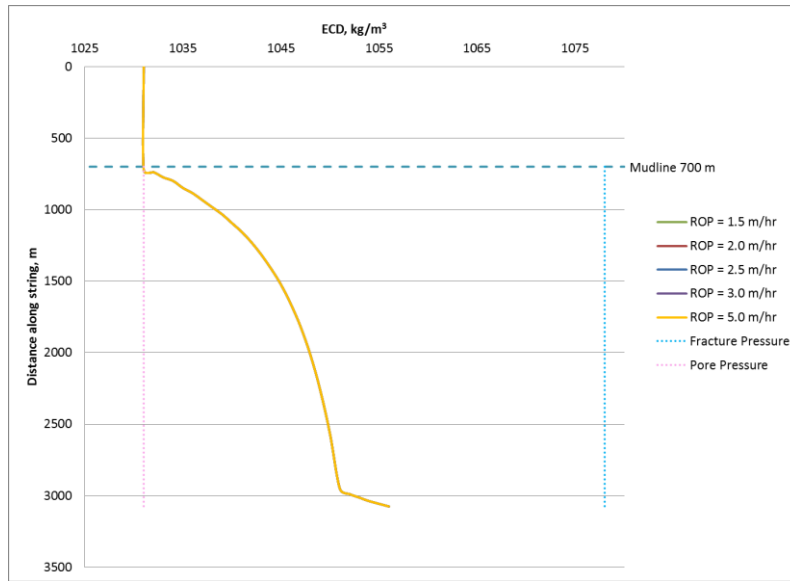


Fig. A.7 – Changing ROP did not result in a change in ECD for 2375 mbsf using gel sweeps. The ECD does increase faster using gel sweeps than saltwater, but stays well within the operating window. The increase in ECD across the bit can also be seen using gel sweeps.

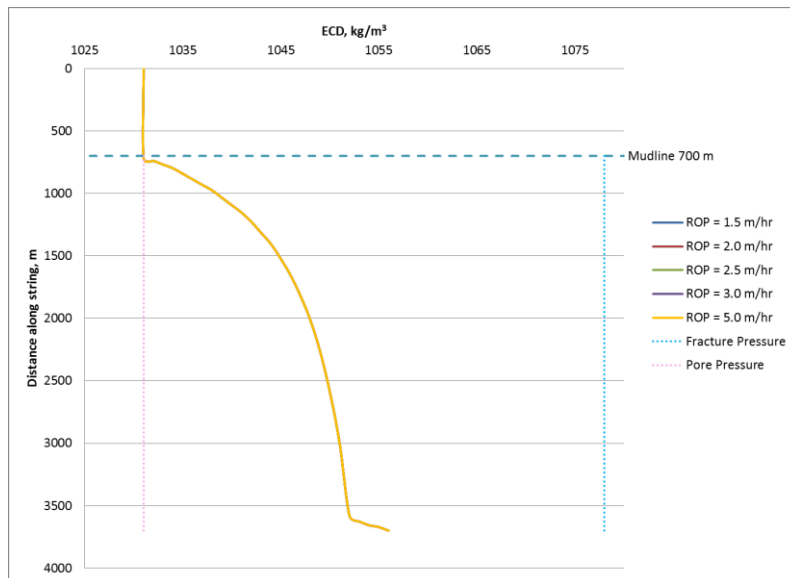


Fig. A.8 - Changing ROP did not result in a change in ECD for 3000 mbsf using gel sweeps. The ECD does increase faster using gel sweeps than saltwater, but stays well within the operating window. The increase in ECD across the bit can also be seen using gel sweeps.

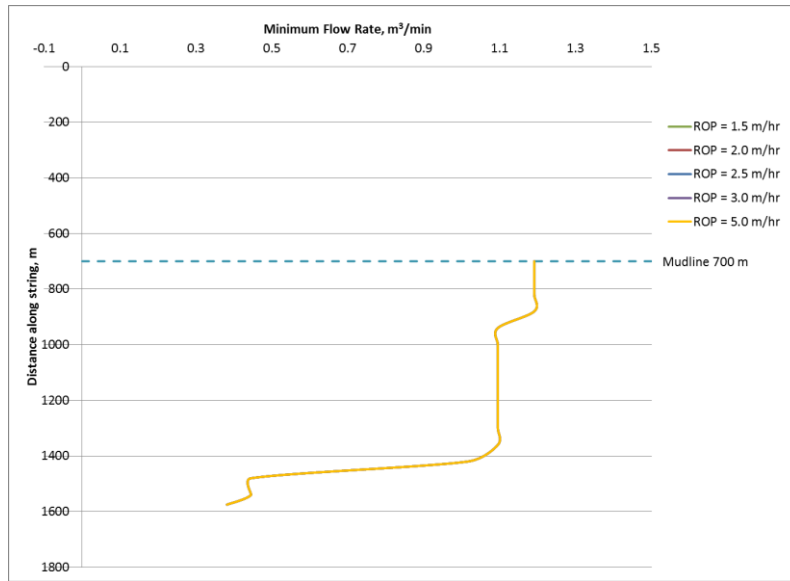


Fig. A.9 – Changing ROP does not change the minimum flow rate required to prevent cutting concentration for 875 mbsf using saltwater. Following the decrease after the casing point, the flow rate remains constant for the majority of the time, with a sharp decrease across the BHA.

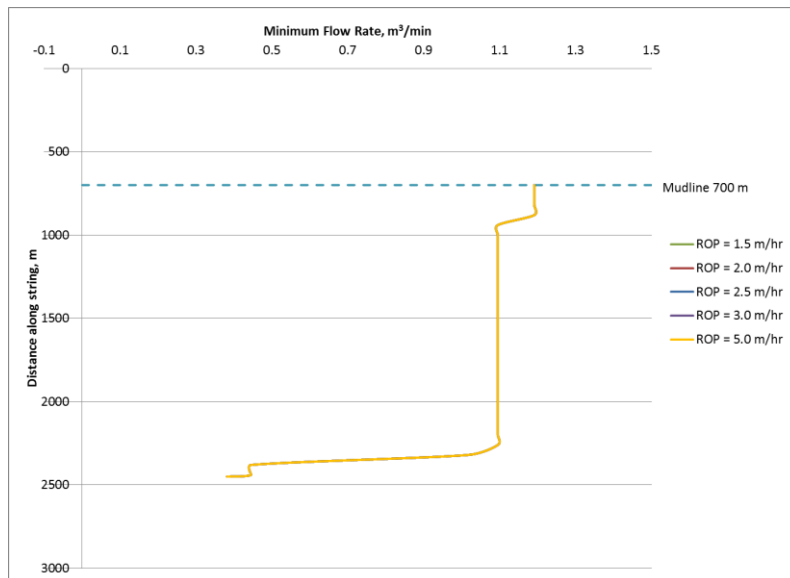


Fig. A.10 – Changing ROP does not change the minimum flow rate required to prevent cutting concentration for 1750 mbsf using saltwater. Following the decrease after the casing point, the flow rate remains constant for the majority of the time, with a sharp decrease across the BHA.

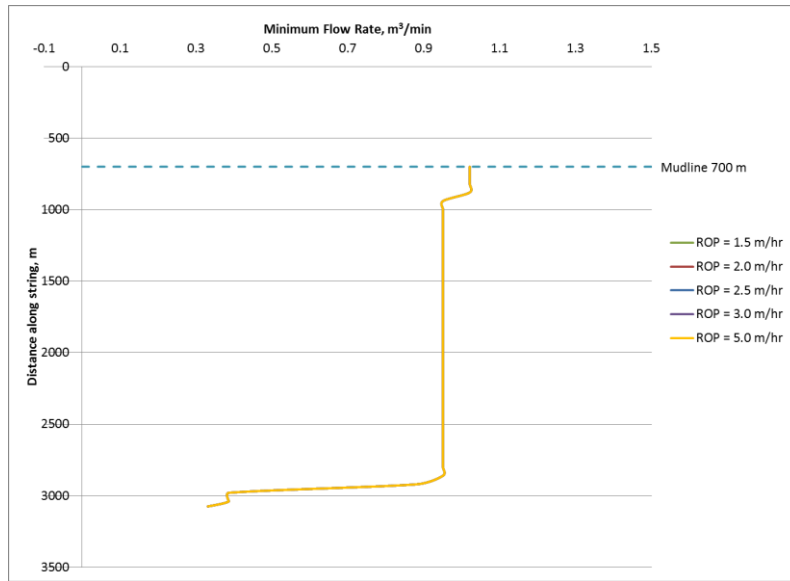


Fig. A.11 – Changing ROP does not change the minimum flow rate required to prevent cutting concentration for 2375 mbsf using saltwater. Following the decrease after the casing point, the flow rate remains constant for the majority of the time, with a sharp decrease across the BHA.

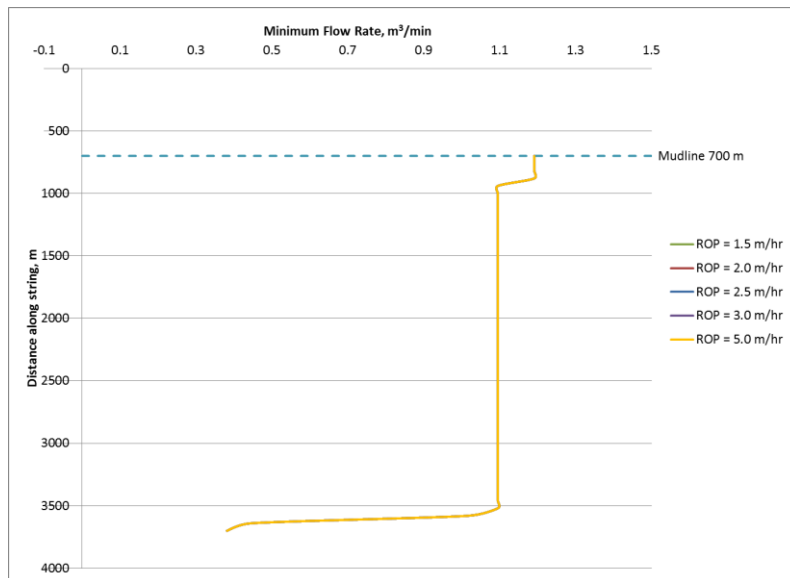


Fig. A.12 – Changing ROP does not change the minimum flow rate required to prevent cutting concentration for 3000 mbsf using saltwater. Following the decrease after the casing point, the flow rate remains constant for the majority of the time, with a sharp decrease across the BHA.

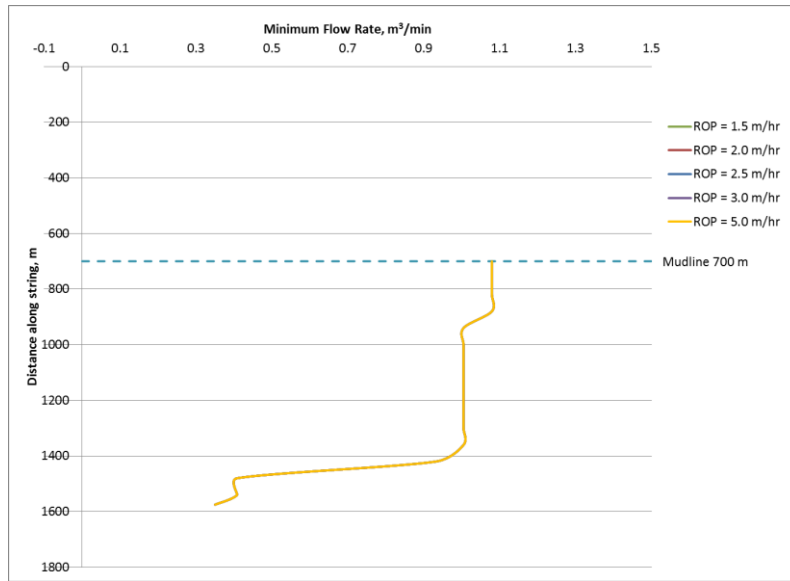


Fig. A.13 – Changing ROP does not change the minimum flow rate required to prevent cutting concentration for 875 mbsf using gel sweeps. Following the decrease after the casing point, the flow rate remains constant for the majority of the time, with a sharp decrease across the BHA. The minimum flow rate remains lower for gel sweeps than saltwater at all depths.

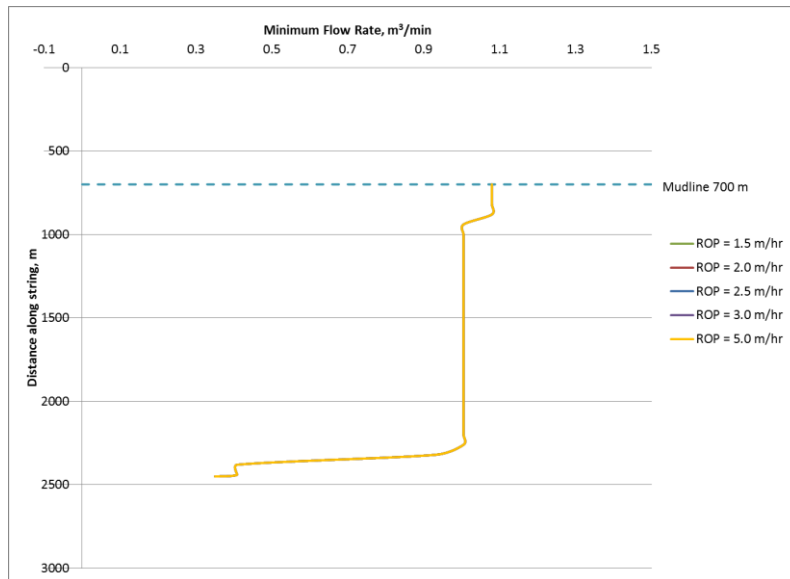


Fig. A.14 – Changing ROP does not change the minimum flow rate required to prevent cutting concentration for 1750 mbsf using gel sweeps. Following the decrease after the casing point, the flow rate remains constant for the majority of the time, with a sharp decrease across the BHA. The minimum flow rate remains lower for gel sweeps than saltwater at all depths.

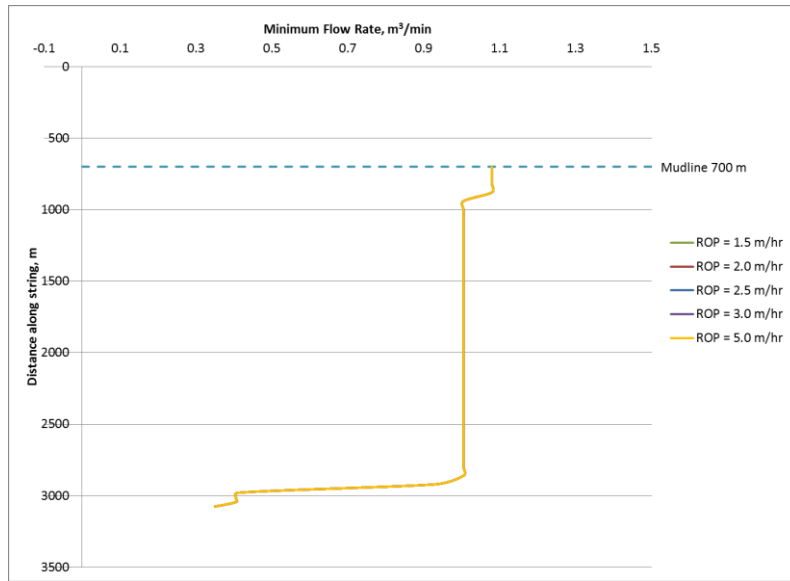


Fig. A.15 – Changing ROP does not change the minimum flow rate required to prevent cutting concentration for 2375 mbsf using gel sweeps. Following the decrease after the casing point, the flow rate remains constant for the majority of the time, with a sharp decrease across the BHA. The minimum flow rate remains lower for gel sweeps than saltwater at all depths.

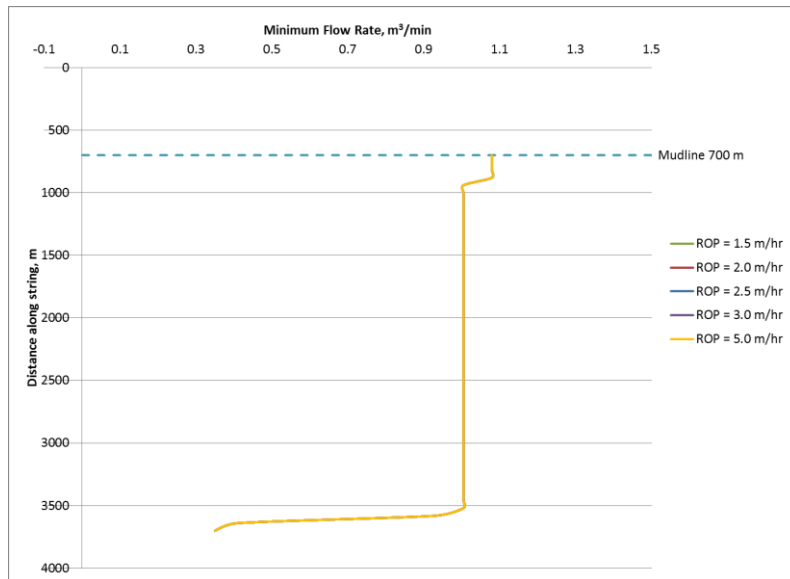


Fig. A.16 – Changing ROP does not change the minimum flow rate required to prevent cutting concentration for 3000 mbsf using gel sweeps. Following the decrease after the casing point, the flow rate remains constant for the majority of the time, with a sharp decrease across the BHA. The minimum flow rate remains lower for gel sweeps than saltwater at all depths.

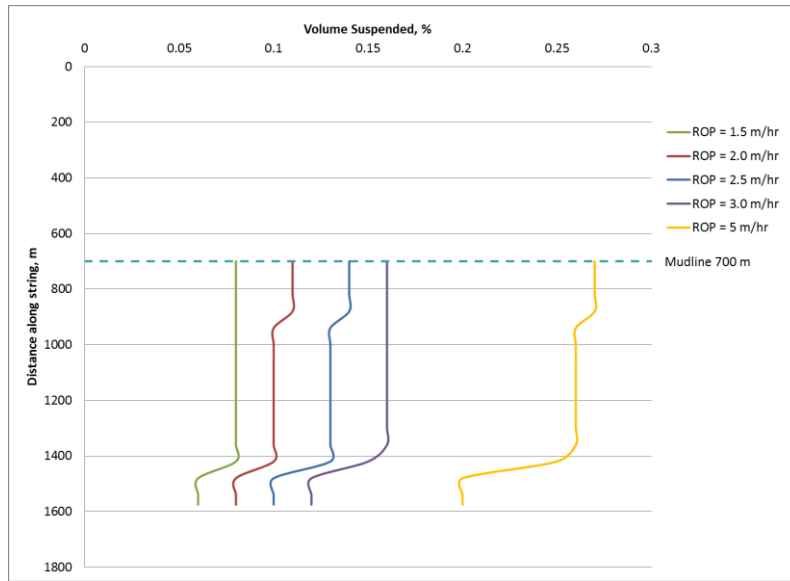


Fig. A.17 – Shows that increasing the ROP increases the amount of cutting volume percentage suspended in the annulus using saltwater as drilling fluid for 875 mbsf. With increasing ROP's, more cuttings will be created and cutting concentration will increase faster with the remaining parameters being constant.

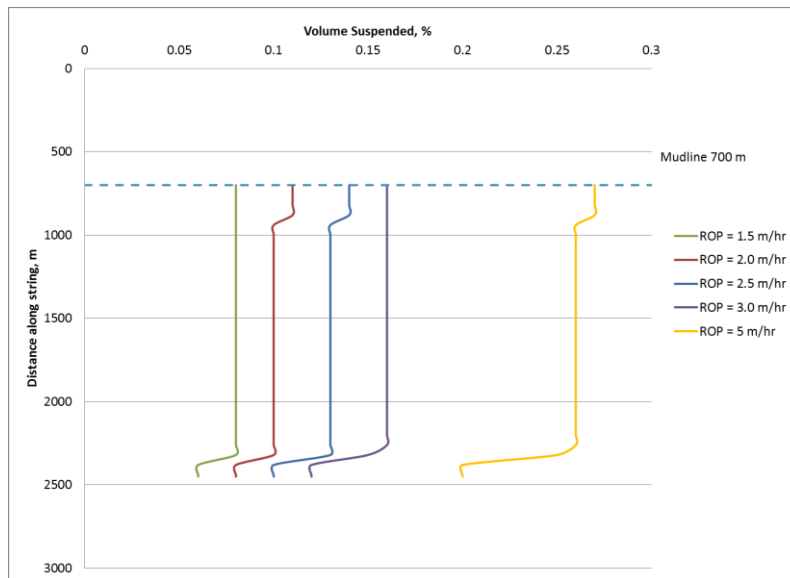


Fig. A.18 – Shows that increasing the ROP increases the amount of cutting volume percentage suspended in the annulus using saltwater as drilling fluid for 1750 mbsf. With increasing ROP's, more cuttings will be created and cutting concentration will increase faster with the remaining parameters being constant.

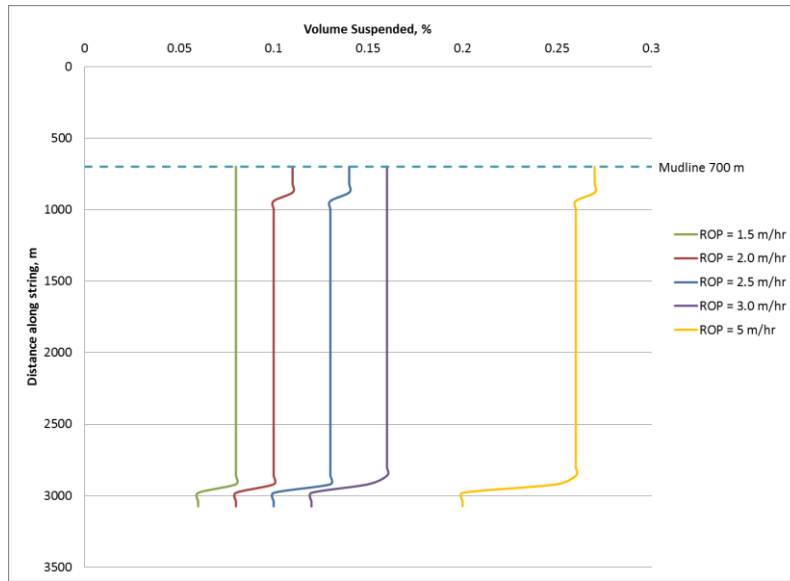


Fig. A.19 – Shows that increasing the ROP increases the amount of cutting volume percentage suspended in the annulus using saltwater as drilling fluid for 2375 mbsf. With increasing ROP's, more cuttings will be created and cutting concentration will increase faster with the remaining parameters being constant.

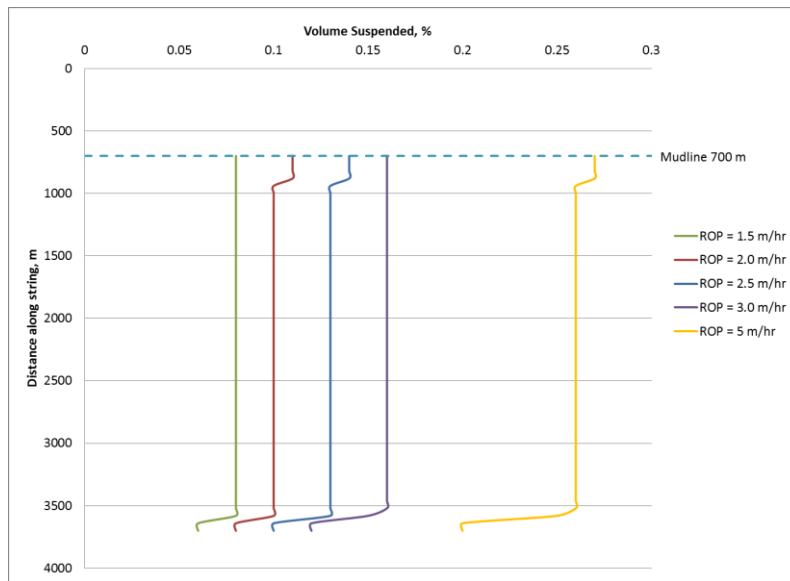


Fig. A.20 – Shows that increasing the ROP increases the amount of cutting volume percentage suspended in the annulus using saltwater as drilling fluid for 3000 mbsf. With increasing ROP's, more cuttings will be created and cutting concentration will increase faster with the remaining parameters being constant.

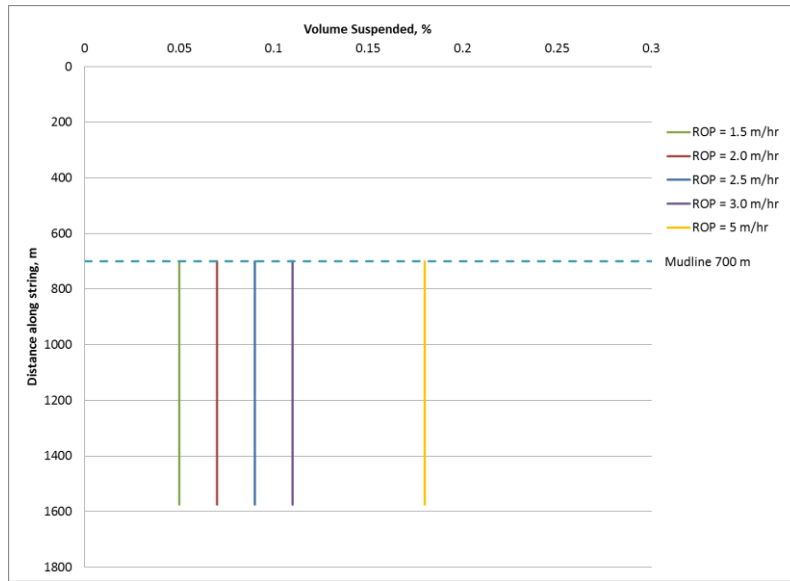


Fig. A.21 – Shows that increasing ROP increases the amount of cutting volume percentage suspended using gel sweeps for 875 mbsf. The gel sweeps generate a lower percentage of cuttings suspended than saltwater and maintain a constant percentage instead of decreasing across the BHA.

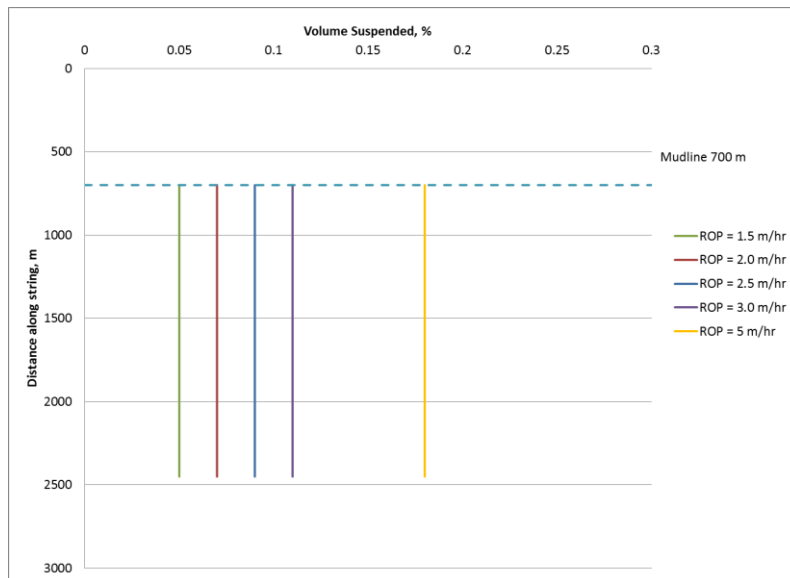


Fig. A.22 – Shows that increasing ROP increases the amount of cutting volume percentage suspended using gel sweeps for 1750 mbsf. The gel sweeps generate a lower percentage of cuttings suspended than saltwater and maintain a constant percentage instead of decreasing across the BHA.

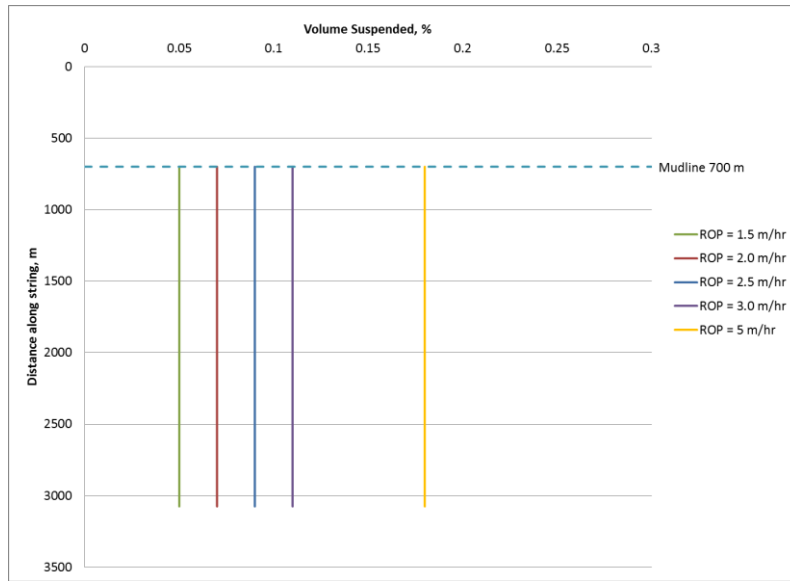


Fig. A.23 – Shows that increasing ROP increases the amount of cutting volume percentage suspended using gel sweeps for 2375 mbsf. The gel sweeps generate a lower percentage of cuttings suspended than saltwater and maintain a constant percentage instead of decreasing across the BHA.

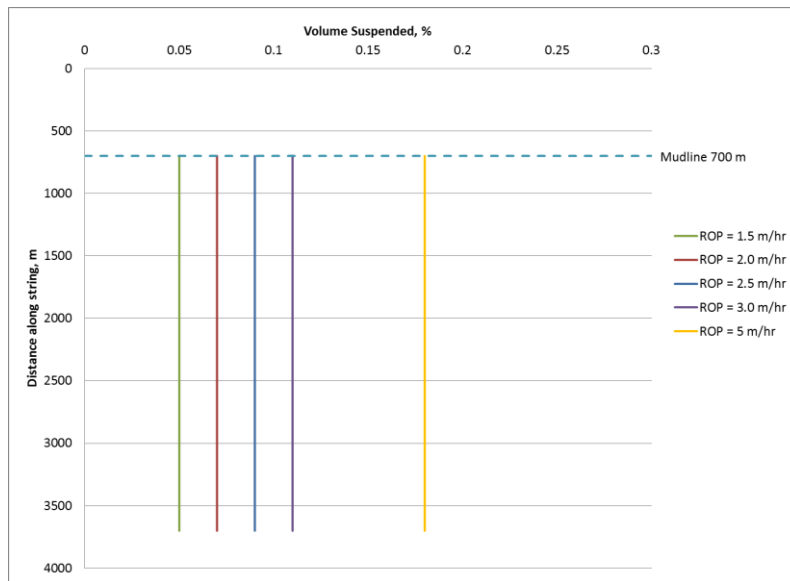


Fig. A.24 – Shows that increasing ROP increases the amount of cutting volume percentage suspended using gel sweeps for 3000 mbsf. The gel sweeps generate a lower percentage of cuttings suspended than saltwater and maintain a constant percentage instead of decreasing across the BHA.

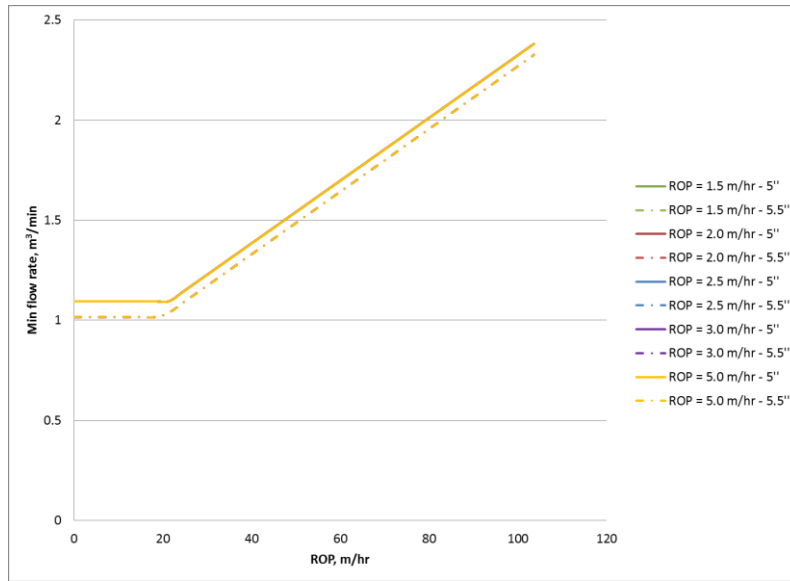


Fig. A.25 – The minimum flow rate required to clean the hole remains constant for ROP's up to 20 m/hr, but then increase linearly for saltwater at 875 mbsf. The 5 inch drill pipe also requires a higher flow rate than the 5 ½ inch drill pipe at all different ROP's.

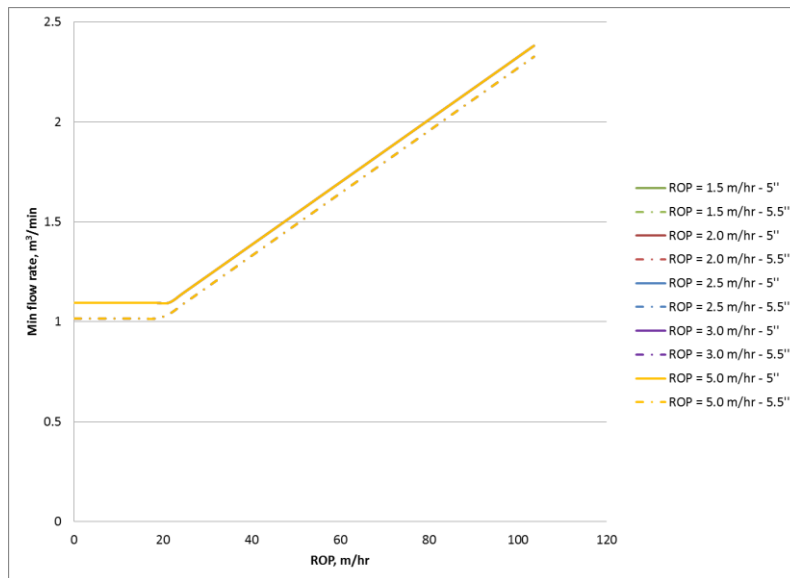


Fig. A.26 – The minimum flow rate required to clean the hole remains constant for ROP's up to 20 m/hr, but then increase linearly for saltwater at 1750 mbsf. The 5 inch drill pipe also requires a higher flow rate than the 5 ½ inch drill pipe at all different ROP's.

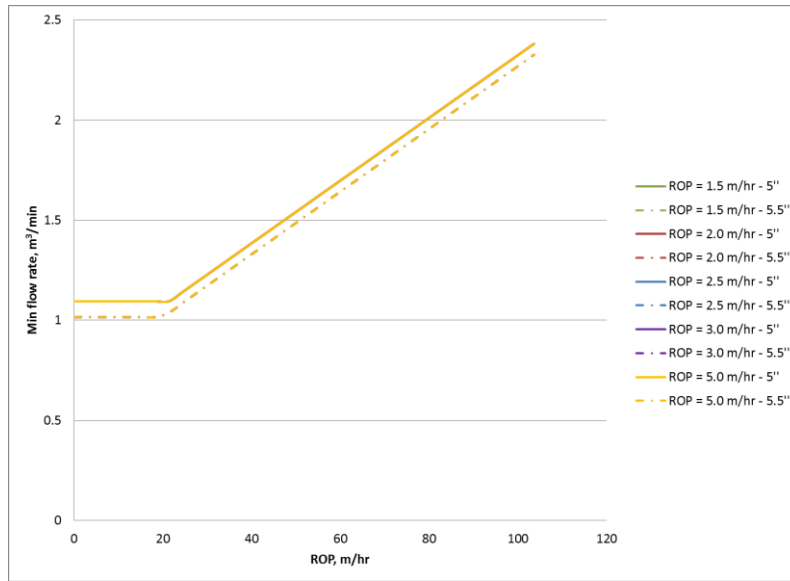


Fig. A.27 – The minimum flow rate required to clean the hole remains constant for ROP's up to 20 m/hr, but then increase linearly for saltwater at 2375 mbsf. The 5 inch drill pipe also requires a higher flow rate than the 5 ½ inch drill pipe at all different ROP's.

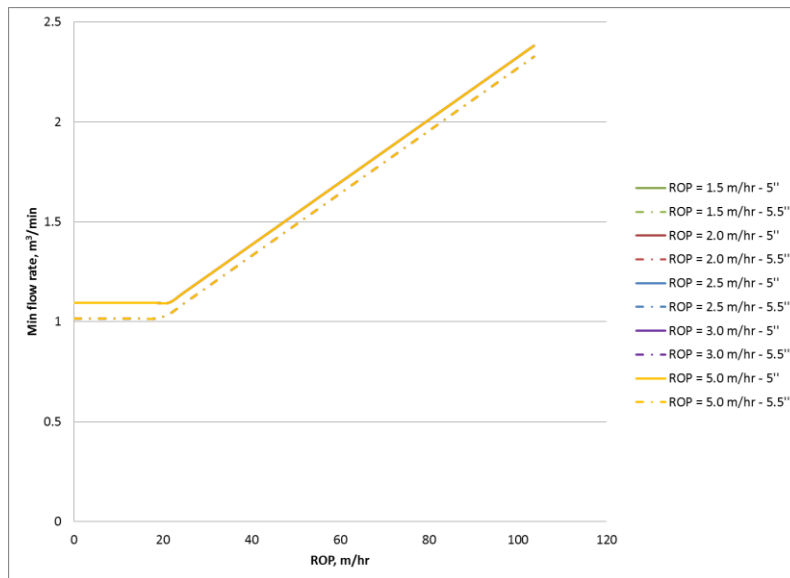


Fig. A.28 – The minimum flow rate required to clean the hole remains constant for ROP's up to 20 m/hr, but then increase linearly for saltwater at 3000 mbsf. The 5 inch drill pipe also requires a higher flow rate than the 5 ½ inch drill pipe at all different ROP's.

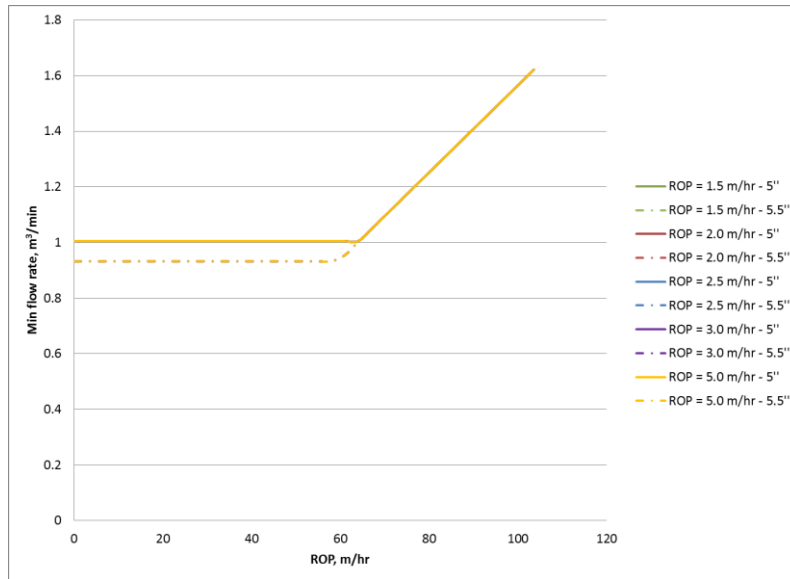


Fig. A.29 – The minimum flow rate required to clean the hole remains constant for ROP's up to 50 m/hr, but then increase linearly for gel sweeps at 875 mbsf. The 5" drill pipe require a higher flow rate for ROP's between 0 and 50 m/hr, but past 50 m/hr the flow rate for 5" and 5 ½" drill pipe remain the same using gel sweeps.

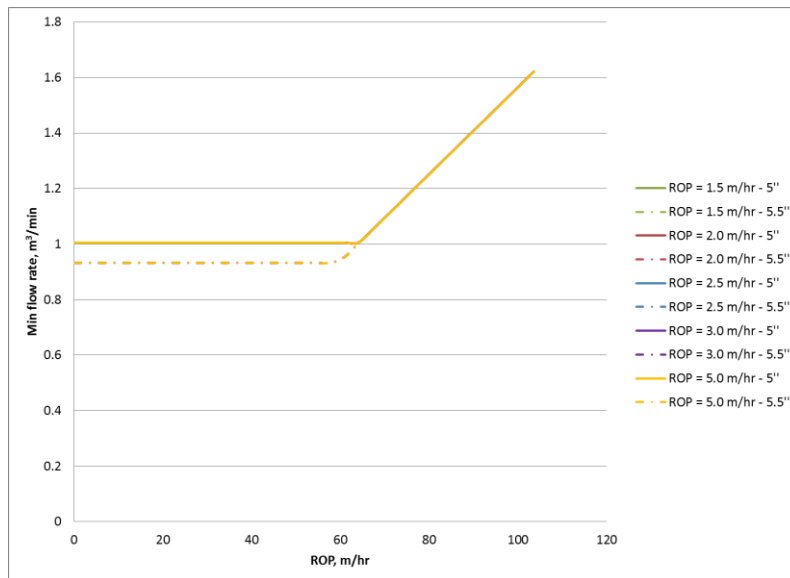


Fig. A.30 – The minimum flow rate required to clean the hole remains constant for ROP's up to 50 m/hr, but then increase linearly for gel sweeps at 1750 mbsf. The 5" drill pipe require a higher flow rate for ROP's between 0 and 50 m/hr, but past 50 m/hr the flow rate for 5" and 5 ½" drill pipe remain the same using gel sweeps.

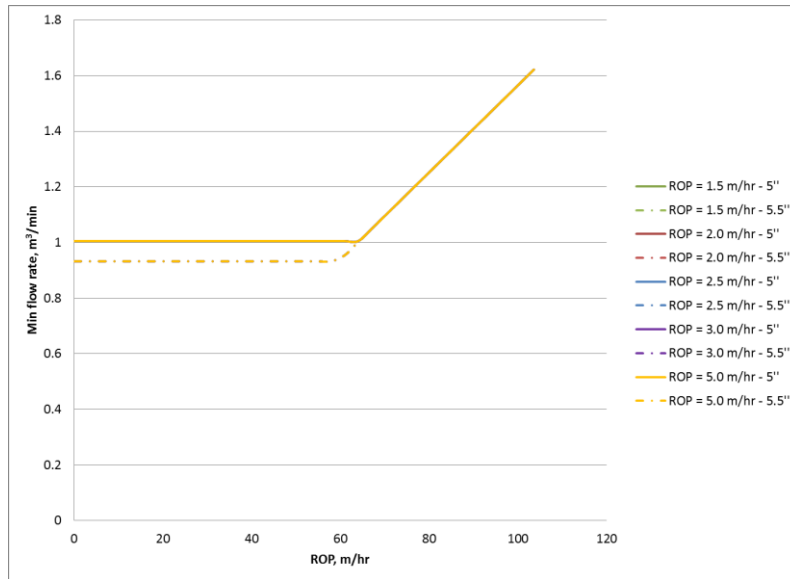


Fig. A.31 – The minimum flow rate required to clean the hole remains constant for ROP's up to 50 m/hr, but then increase linearly for gel sweeps at 2375 mbsf. The 5" drill pipe require a higher flow rate for ROP's between 0 and 50 m/hr, but past 50 m/hr the flow rate for 5" and 5 ½" drill pipe remain the same using gel sweeps.

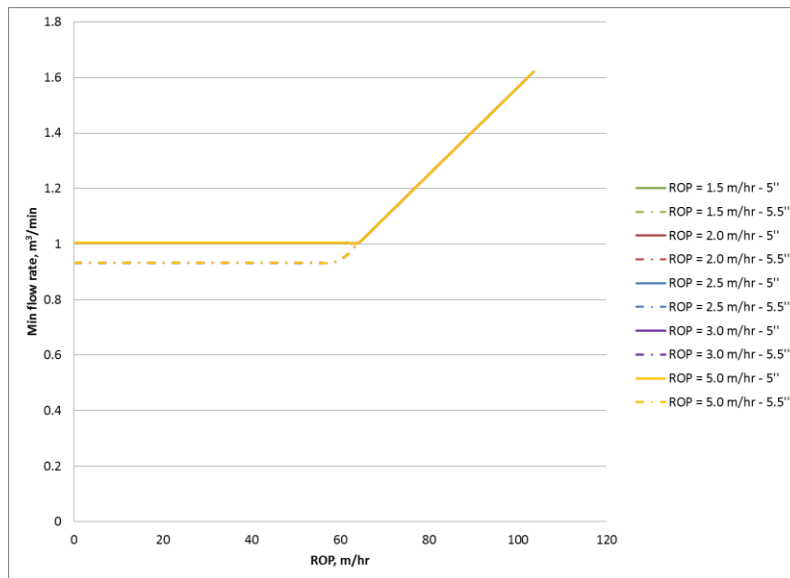


Fig. A.32 – The minimum flow rate required to clean the hole remains constant for ROP's up to 50 m/hr, but then increase linearly for gel sweeps at 875 mbsf. The 5" drill pipe require a higher flow rate for ROP's between 0 and 50 m/hr, but past 50 m/hr the flow rate for 5" and 5 ½" drill pipe remain the same using gel sweeps.

APPENDIX B

RESULTS FOR CHANGING PUMP RATE

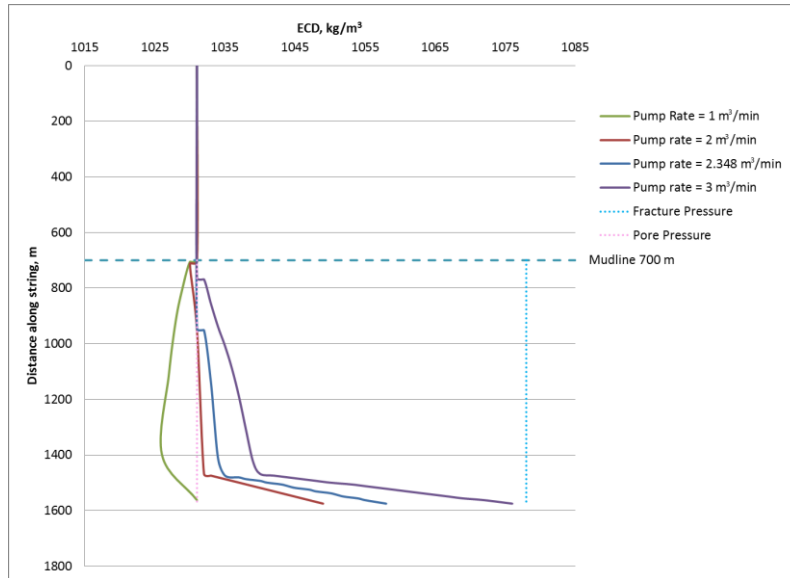


Fig. B.1 – Shows that the increase in pump rate increases the ECD using saltwater at 875 mbsf. With a pump rate of less than 2.348 m³/min, the ECD falls below the pore pressure which can result in an influx or kick. The increase in ECD is very large across the bit, but stays within the operating window for 2.348 and 3 m³/min.

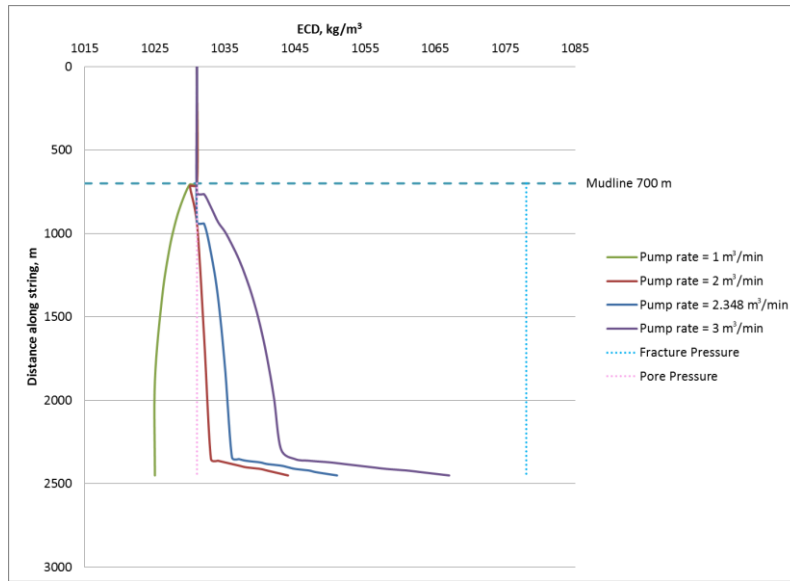


Fig. B.2 – Shows that the increase in pump rate increases the ECD using saltwater at 1750 mbsf. With a pump rate of less than 2.348 m³/min, the ECD falls below the pore pressure which can result in an influx or kick. The increase in ECD is very large across the bit, but stays within the operating window for 2.348 and 3 m³/min.

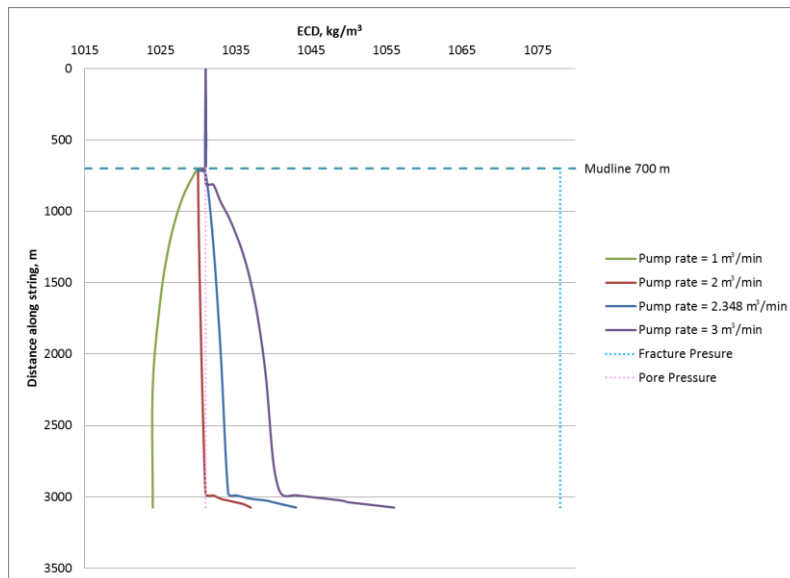


Fig. B.3 – Shows that the increase in pump rate increases the ECD using saltwater at 2375 mbsf. With a pump rate of less than 2.348 m³/min, the ECD falls below the pore pressure which can result in an influx or kick. The increase in ECD is larger across the bit, but stays well within the operating window for 2.348 and 3 m³/min.

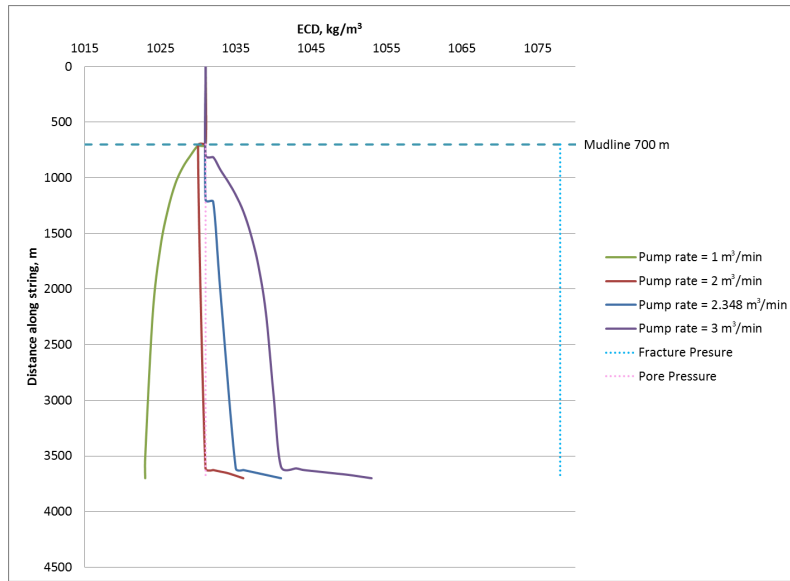


Fig. B.4 - Shows that the increase in pump rate increases the ECD using saltwater at 3000 mbsf. With a pump rate of less than 2.348 m³/min, the ECD falls below the pore pressure which can result in an influx or kick. The increase in ECD is larger across the bit, but stays well within the operating window for 2.348 and 3 m³/min.

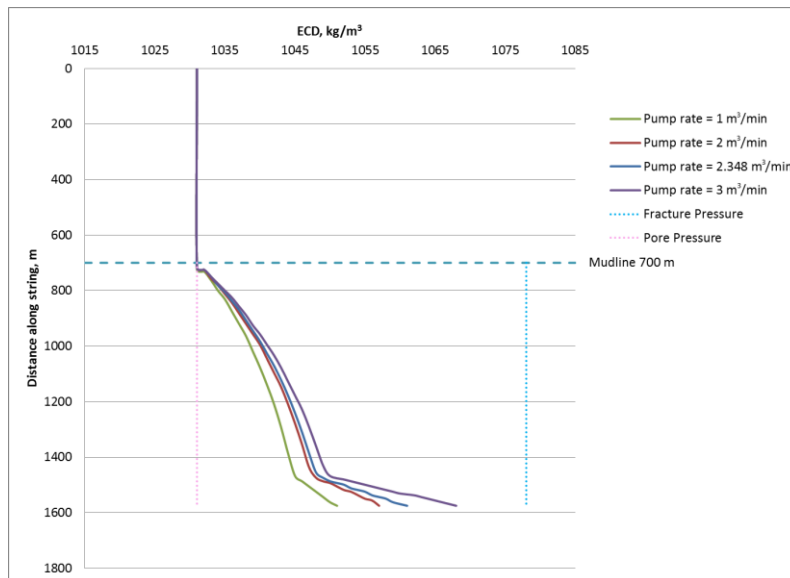


Fig. B.5 - Shows that the increase in pump rate increases the ECD using gel sweeps at 875 mbsf. The ECD using gel sweeps stays well within the operating window at all depths for all pump rates.

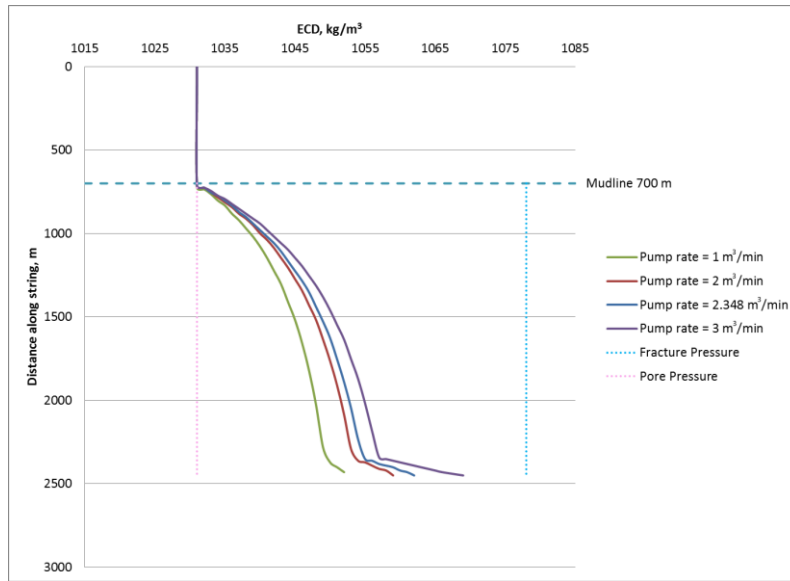


Fig. B.6 - Shows that the increase in pump rate increases the ECD using gel sweeps at 1750 mbsf. The ECD using gel sweeps stays well within the operating window at all depths for all pump rates.

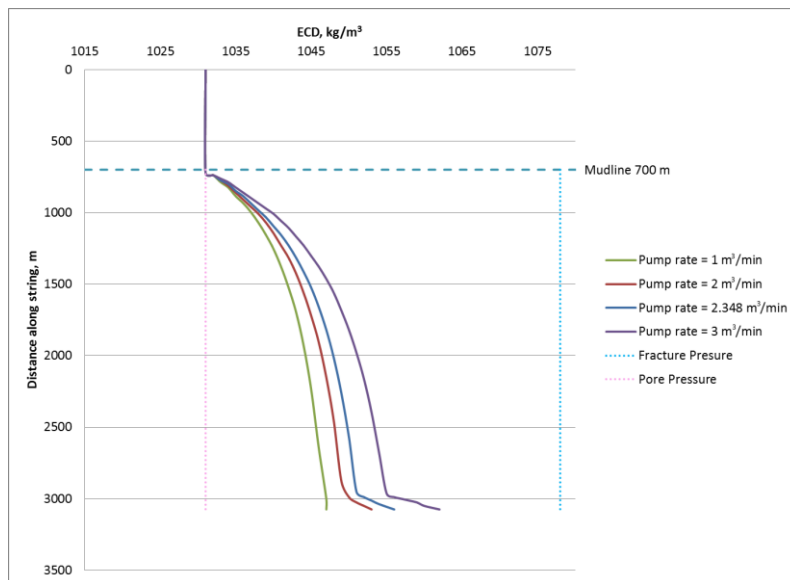


Fig. B.7 - Shows that the increase in pump rate increases the ECD using gel sweeps at 2375 mbsf. The ECD using gel sweeps stays well within the operating window at all depths for all pump rates.

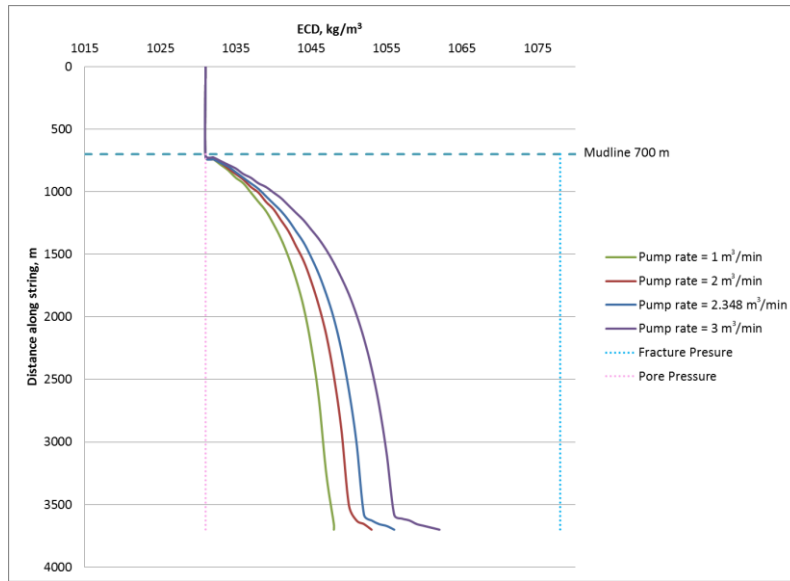


Fig. B.8 - Shows that the increase in pump rate increases the ECD using gel sweeps at 3000 mbsf. The ECD using gel sweeps stays well within the operating window at all depths for all pump rates.

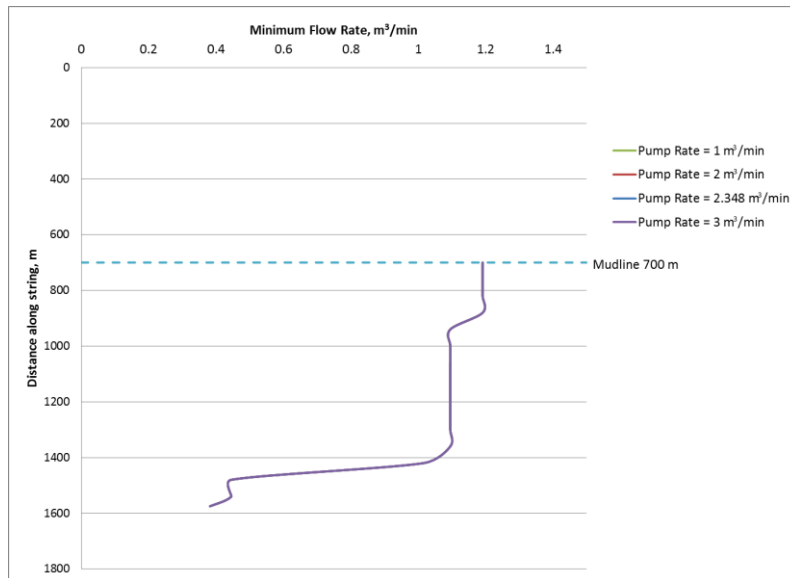


Fig. B.9 - Changing pump rate does not change the minimum flow rate required to prevent cutting concentration for 875 mbsf using saltwater. Following the decrease after the casing point, the flow rate remains constant for the majority of the time, with a sharp decrease across the BHA.

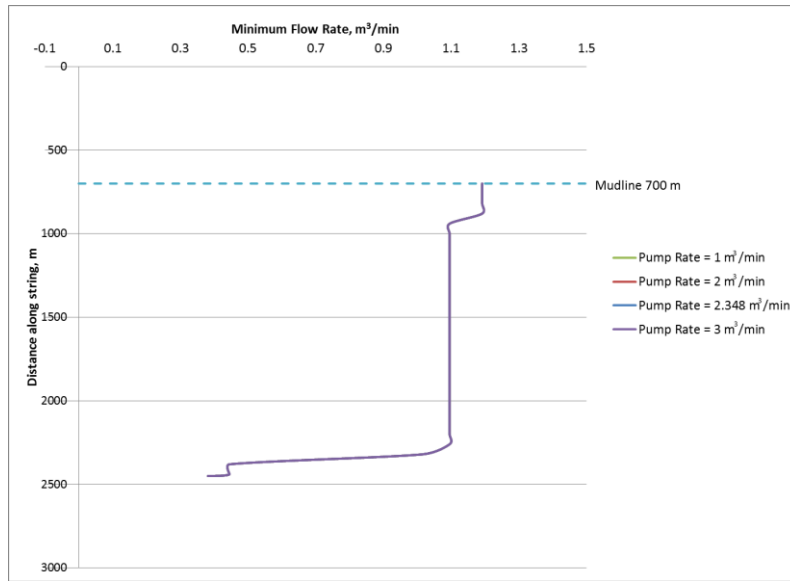


Fig. B.10 - Changing pump rate does not change the minimum flow rate required to prevent cutting concentration for 1750 mbsf using saltwater. Following the decrease after the casing point, the flow rate remains constant for the majority of the time, with a sharp decrease across the BHA.

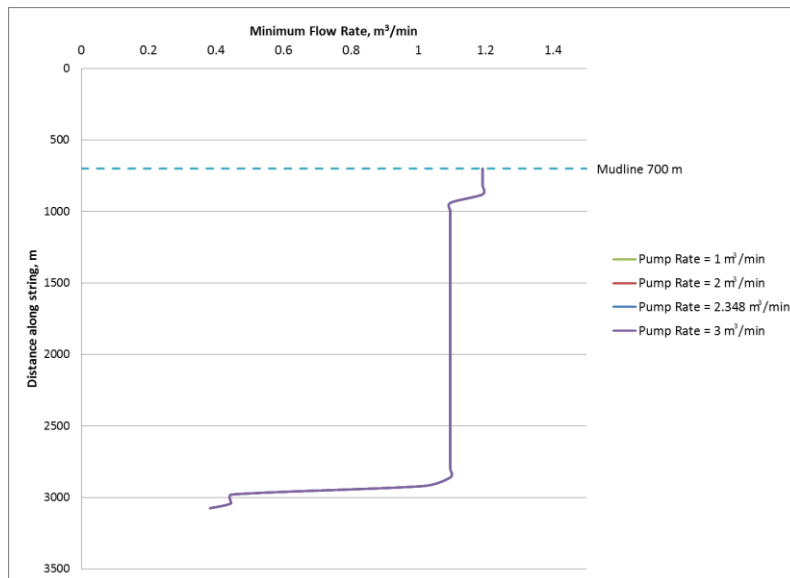


Fig. B.11 - Changing pump rate does not change the minimum flow rate required to prevent cutting concentration for 2375 mbsf using saltwater. Following the decrease after the casing point, the flow rate remains constant for the majority of the time, with a sharp decrease across the BHA.

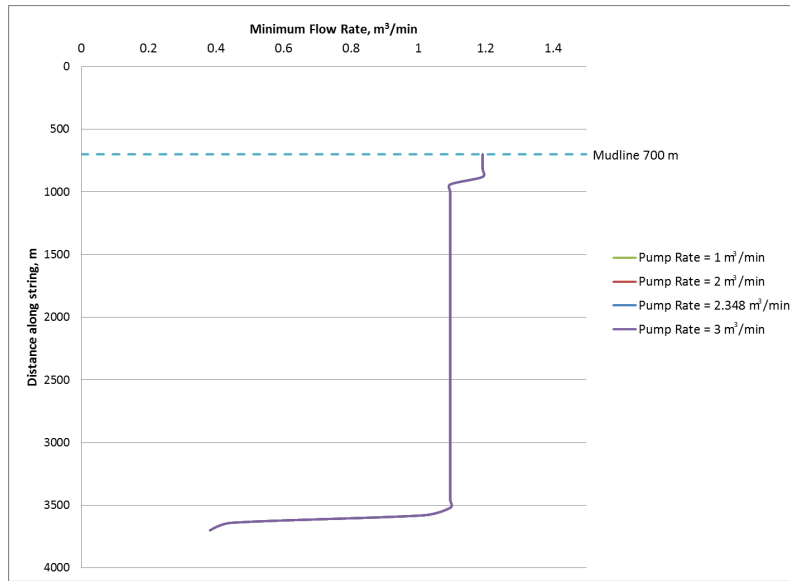


Fig. B.12 - Changing pump rate does not change the minimum flow rate required to prevent cutting concentration for 3000 mbsf using saltwater. Following the decrease after the casing point, the flow rate remains constant for the majority of the time, with a sharp decrease across the BHA.

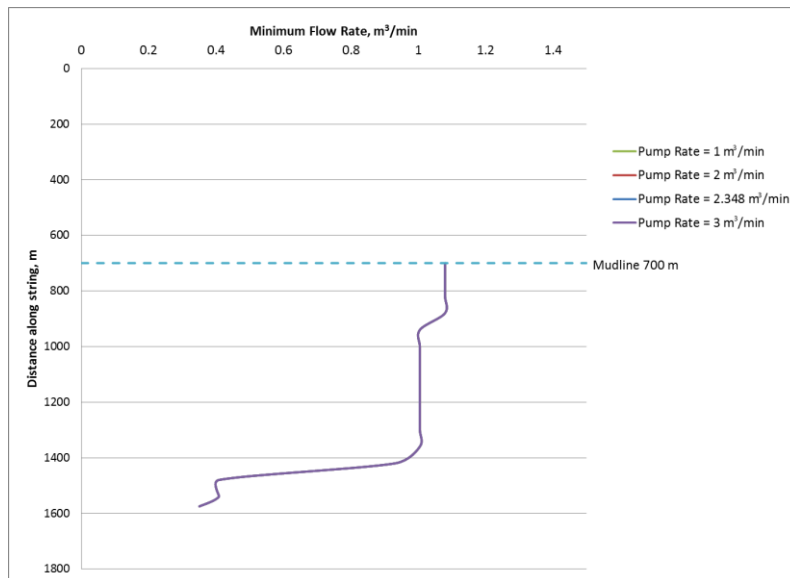


Fig. B.13 - Changing pump rate does not change the minimum flow rate required to prevent cutting concentration for 875 mbsf using gel sweeps. Following the decrease after the casing point, the flow rate remains constant for the majority of the time, with a sharp decrease across the BHA. The minimum flow rate remains slightly lower for gel sweeps than saltwater at all depths.

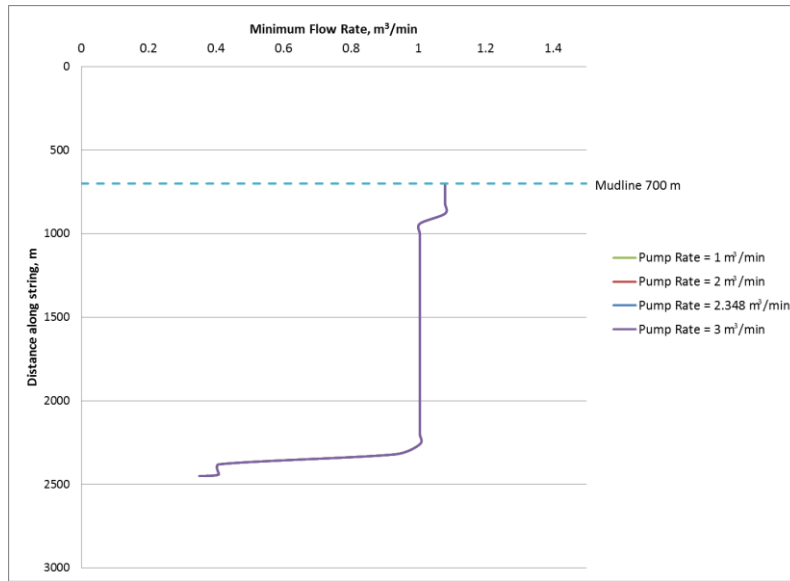


Fig. B.14 - Changing pump rate does not change the minimum flow rate required to prevent cutting concentration for 1750 mbsf using gel sweeps. Following the decrease after the casing point, the flow rate remains constant for the majority of the time, with a sharp decrease across the BHA. The minimum flow rate remains slightly lower for gel sweeps than saltwater at all depths.

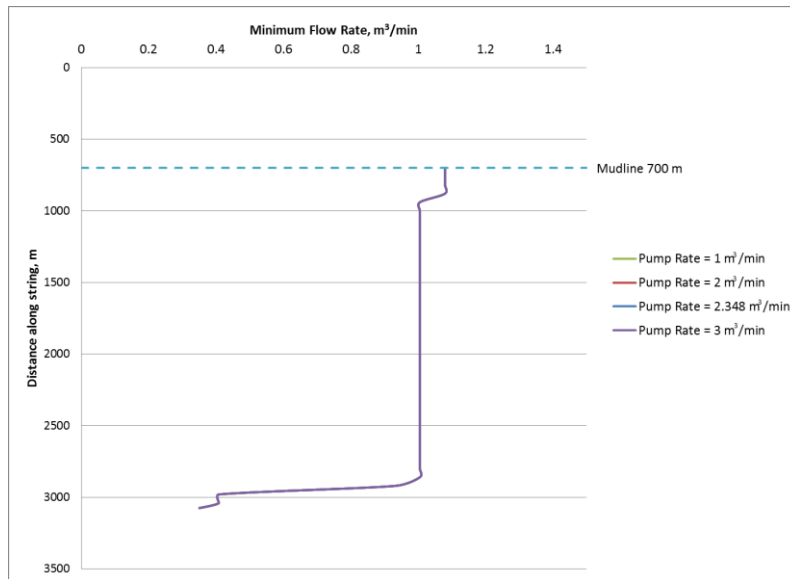


Fig. B.15 - Changing pump rate does not change the minimum flow rate required to prevent cutting concentration for 2375 mbsf using gel sweeps. Following the decrease after the casing point, the flow rate remains constant for the majority of the time, with a sharp decrease across the BHA. The minimum flow rate remains slightly lower for gel sweeps than saltwater at all depths.

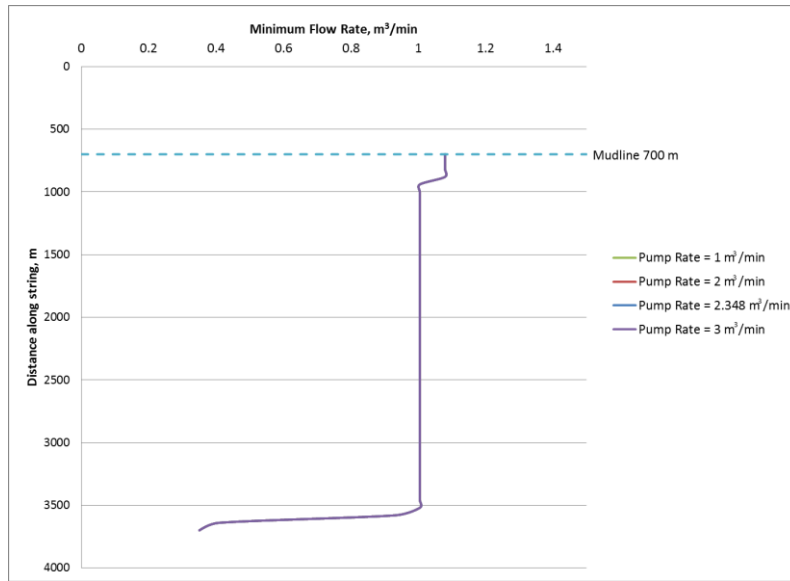


Fig. B.16 - Changing pump rate does not change the minimum flow rate required to prevent cutting concentration for 3000 mbsf using gel sweeps. Following the decrease after the casing point, the flow rate remains constant for the majority of the time, with a sharp decrease across the BHA. The minimum flow rate remains slightly lower for gel sweeps than saltwater at all depths.

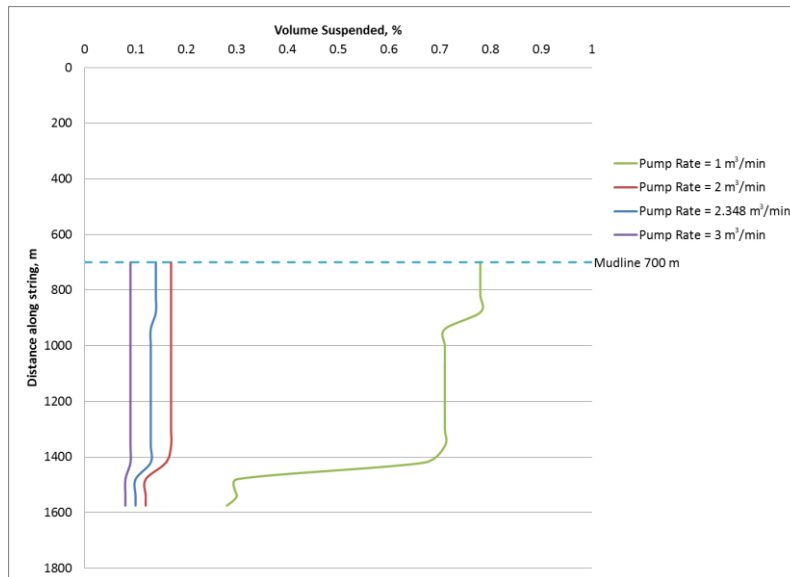


Fig. B.17 – Shows that decreasing the pump rate increases the amount of cutting percentage suspended in the annulus using saltwater at 875 mbsf. With increasing pump rates, the annular velocity will increase, preventing cuttings from settling in the annulus. With a low pump pressure of 1 m³/min, the cutting volume suspended is approximately 0.7%.

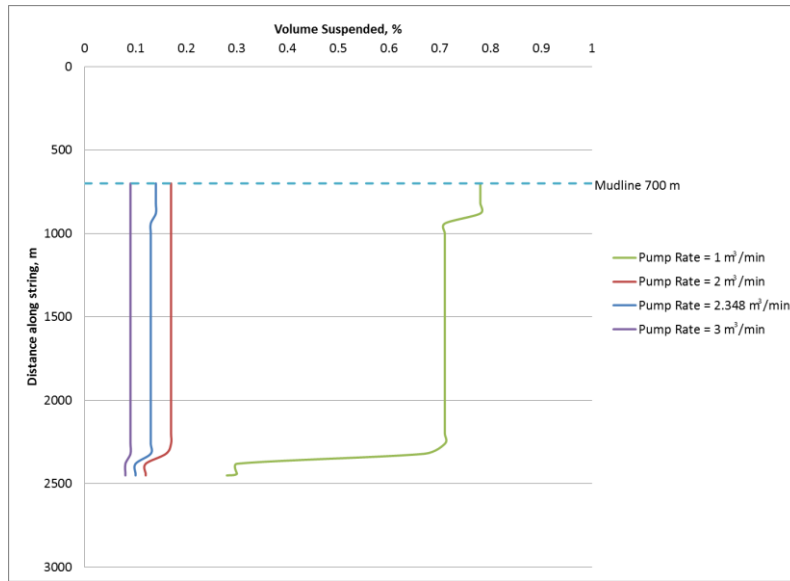


Fig. B.18 – Shows that decreasing the pump rate increases the amount of cutting percentage suspended in the annulus using saltwater at 1750 mbsf. With increasing pump rates, the annular velocity will increase, preventing cuttings from settling in the annulus. With a low pump pressure of 1 m³/min, the cutting volume suspended is approximately 0.7%.

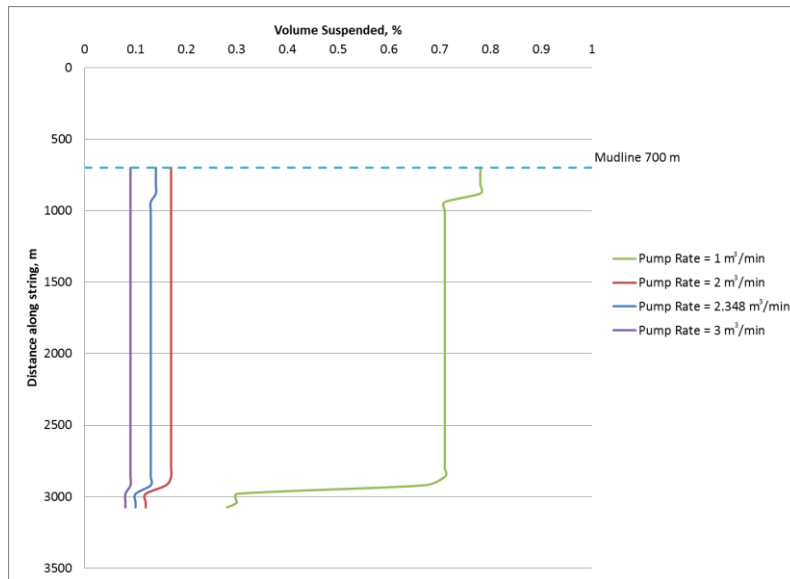


Fig. B.19 – Shows that decreasing the pump rate increases the amount of cutting percentage suspended in the annulus using saltwater at 2375 mbsf. With increasing pump rates, the annular velocity will increase, preventing cuttings from settling in the annulus. With a low pump pressure of 1 m³/min, the cutting volume suspended is approximately 0.7%.

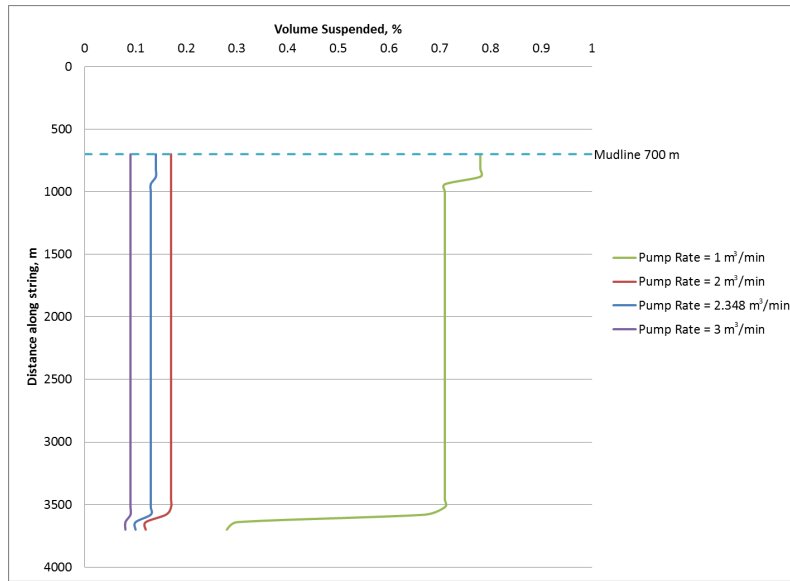


Fig. B.20 – Shows that decreasing the pump rate increases the amount of cutting percentage suspended in the annulus using saltwater at 3000 mbsf. With increasing pump rates, the annular velocity will increase, preventing cuttings from settling in the annulus. With a low pump pressure of 1 m³/min, the cutting volume suspended is approximately 0.7%.

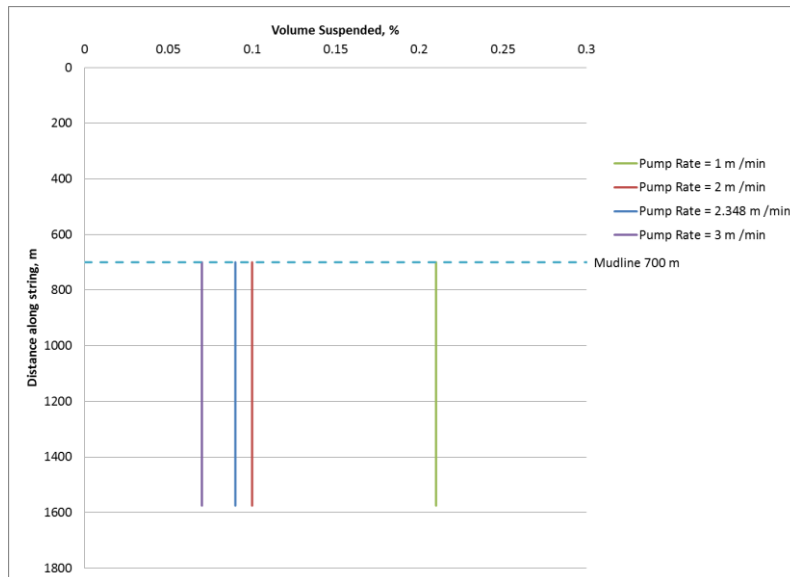


Fig. B.21 – Shows that decreasing the pump rate increases the amount of cutting percentage suspended in the annulus using gel sweeps at 875 mbsf. The gel sweeps generate a lower percentage of cuttings suspended than saltwater and maintain a constant percentage instead of decreasing across the BHA.

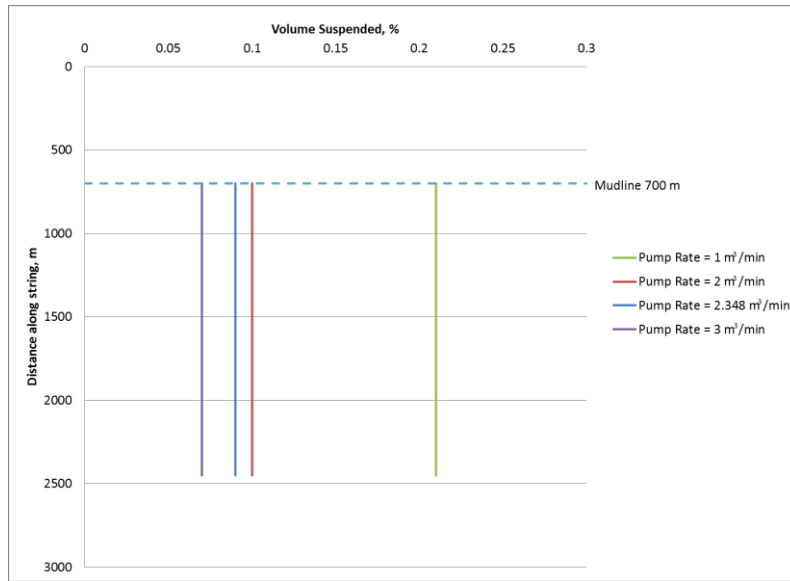


Fig. B.22 – Shows that decreasing the pump rate increases the amount of cutting percentage suspended in the annulus using gel sweeps at 1750 mbsf. The gel sweeps generate a lower percentage of cuttings suspended than saltwater and maintain a constant percentage instead of decreasing across the BHA.

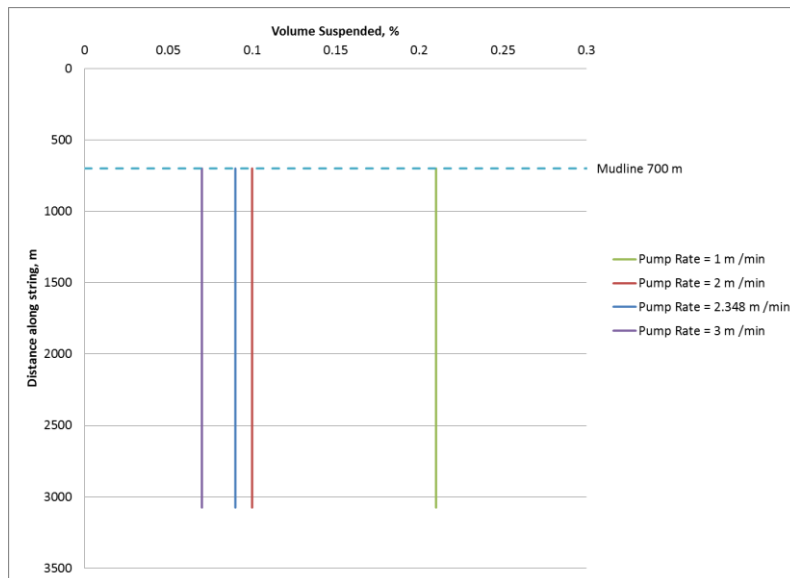


Fig. B.23 – Shows that decreasing the pump rate increases the amount of cutting percentage suspended in the annulus using gel sweeps at 2375 mbsf. The gel sweeps generate a lower percentage of cuttings suspended than saltwater and maintain a constant percentage instead of decreasing across the BHA.

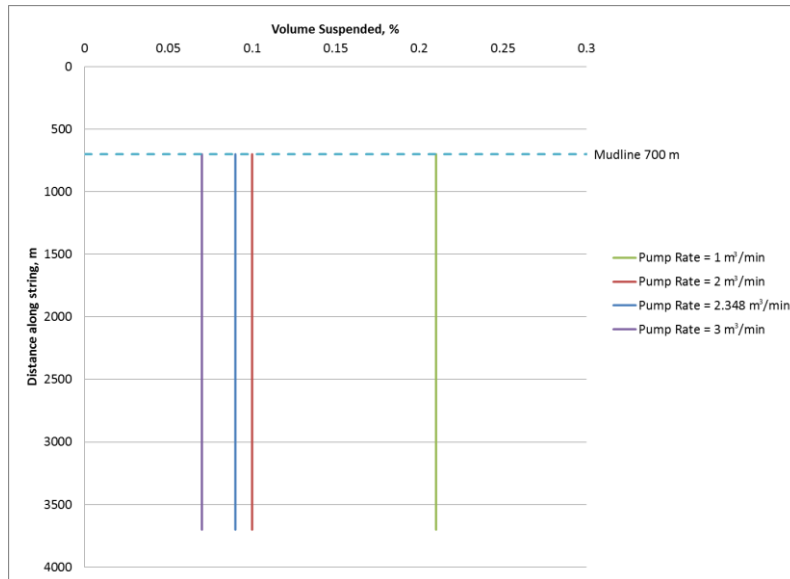


Fig. B.24 – Shows that decreasing the pump rate increases the amount of cutting percentage suspended in the annulus using gel sweeps at 3000 mbsf. The gel sweeps generate a lower percentage of cuttings suspended than saltwater and maintain a constant percentage instead of decreasing across the BHA.

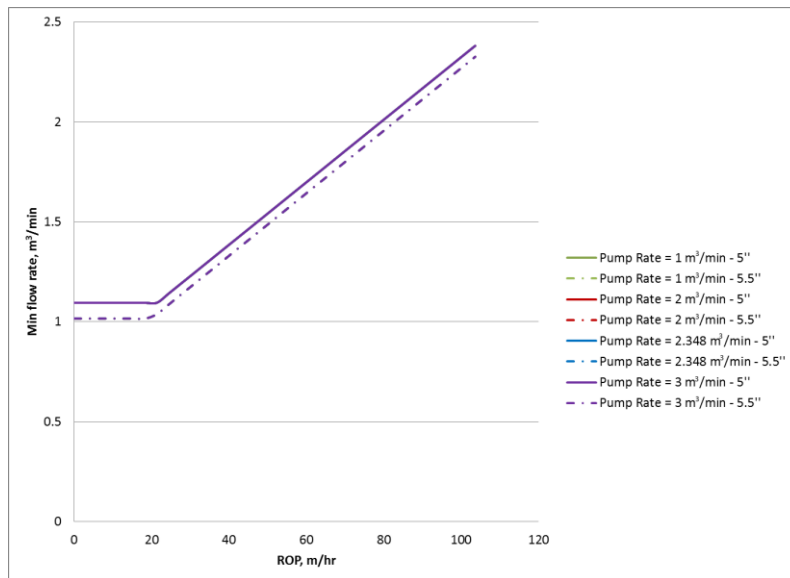


Fig. B.25 – The minimum flow rate required to clean the hole remains constant for ROP's up to 20 m/hr, but then increase linearly for saltwater at 875 mbsf. The 5 inch drill pipe also requires a higher flow rate than the 5 ½ inch drill pipe at all different pump rates.

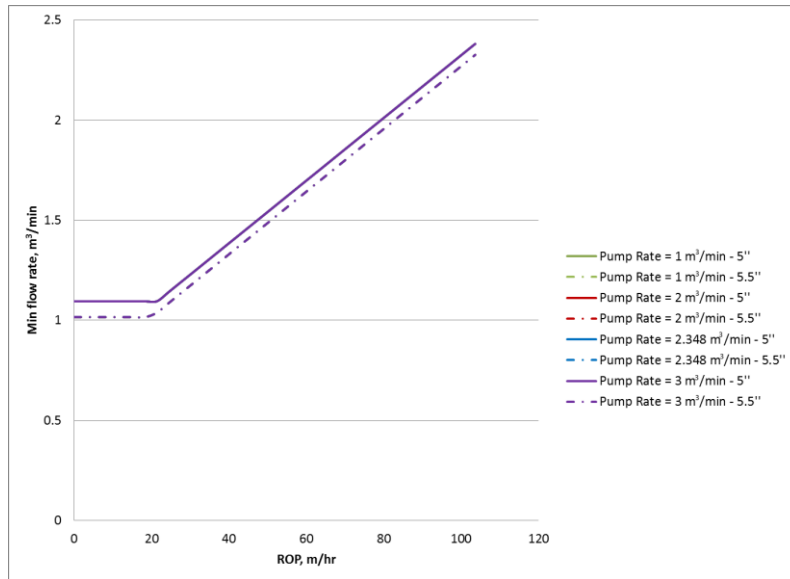


Fig. B.26 – The minimum flow rate required to clean the hole remains constant for ROP's up to 20 m/hr, but then increase linearly for saltwater at 1750 mbsf. The 5 inch drill pipe also requires a higher flow rate than the 5 ½ inch drill pipe at all different pump rates.

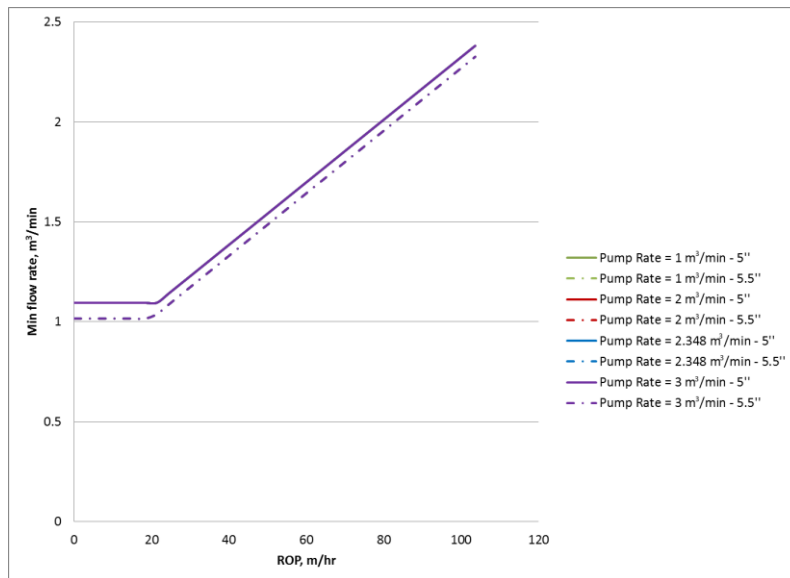


Fig. B.27 – The minimum flow rate required to clean the hole remains constant for ROP's up to 20 m/hr, but then increase linearly for saltwater at 2375 mbsf. The 5 inch drill pipe also requires a higher flow rate than the 5 ½ inch drill pipe at all different pump rates.

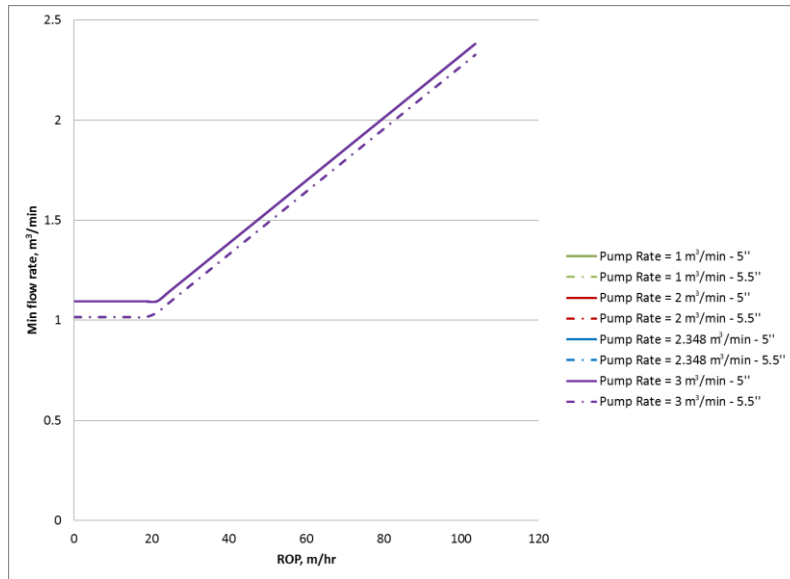


Fig. B.28 – The minimum flow rate required to clean the hole remains constant for ROP's up to 20 m/hr, but then increase linearly for saltwater at 3000 mbsf. The 5 inch drill pipe also requires a higher flow rate than the 5 ½ inch drill pipe at all different pump rates.

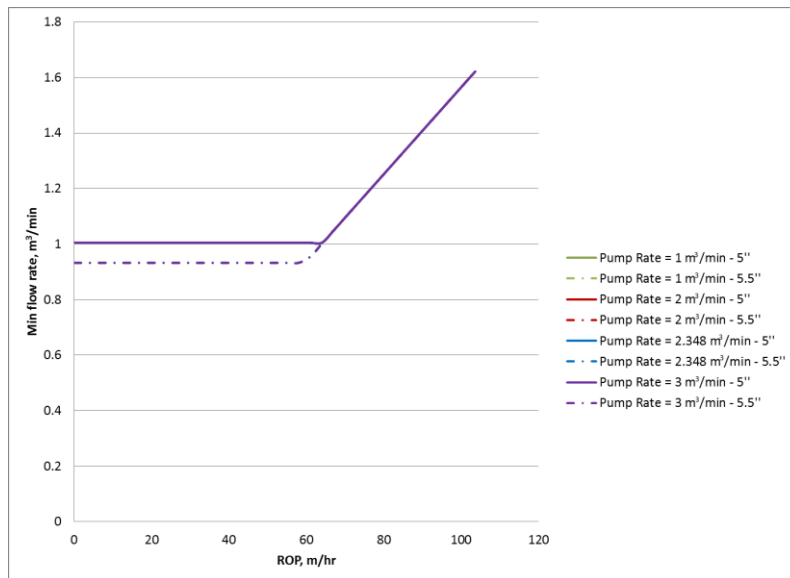


Fig. B.29 – The minimum flow rate required to clean the hole remains constant for ROP's up to 50 m/hr, but then increase linearly for gel sweeps at 875 mbsf. The 5-inch drill pipe requires a higher flow rate for ROP's between 0 and 50 m/hr, but past 50 m/hr the flow rate for 5-inch and 5 ½-inch drill pipe remain the same using gel sweeps.

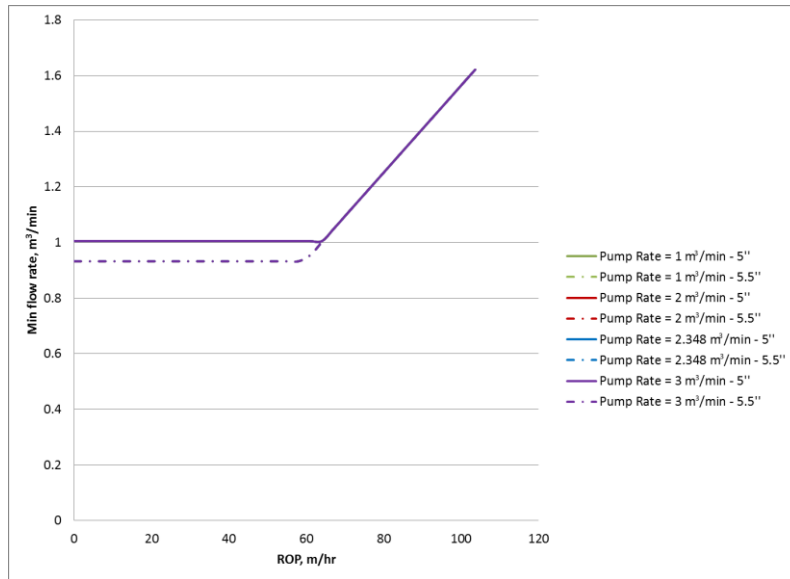


Fig. B.30 – The minimum flow rate required to clean the hole remains constant for ROP's up to 50 m/hr, but then increase linearly for gel sweeps at 1750 mbsf. The 5" drill pipe require a higher flow rate for ROP's between 0 and 50 m/hr, but past 50 m/hr the flow rate for 5" and 5 ½" drill pipe remain the same using gel sweeps.

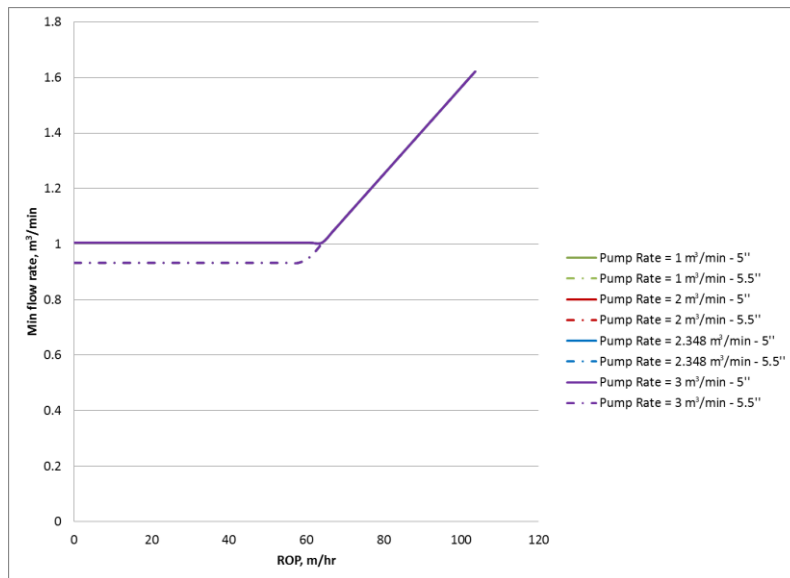


Fig. B.31 – The minimum flow rate required to clean the hole remains constant for ROP's up to 50 m/hr, but then increase linearly for gel sweeps at 2375 mbsf. The 5" drill pipe require a higher flow rate for ROP's between 0 and 50 m/hr, but past 50 m/hr the flow rate for 5" and 5 ½" drill pipe remain the same using gel sweeps.

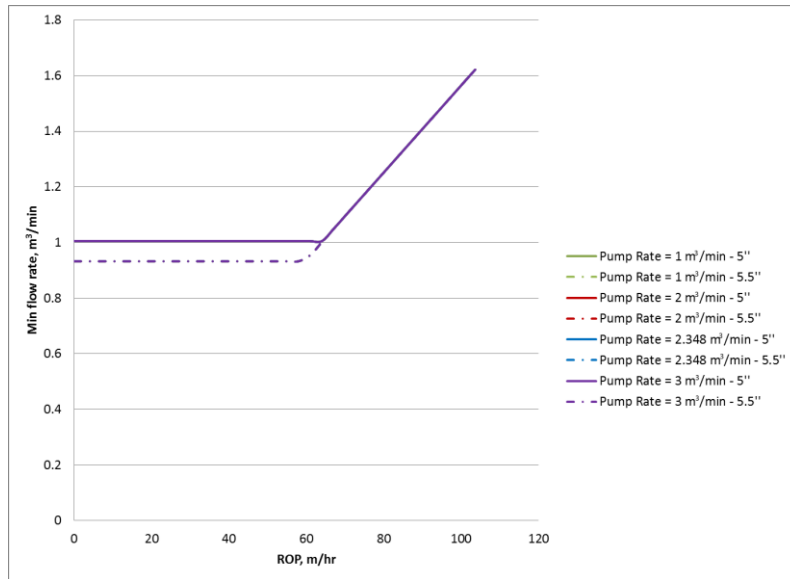


Fig. B.32 – The minimum flow rate required to clean the hole remains constant for ROP's up to 50 m/hr, but then increase linearly for gel sweeps at 3000 mbsf. The 5'' drill pipe require a higher flow rate for ROP's between 0 and 50 m/hr, but past 50 m/hr the flow rate for 5'' and 5 ½'' drill pipe remain the same using gel sweeps.

APPENDIX C

RESULTS FOR CHANGING CUTTING DENSITY

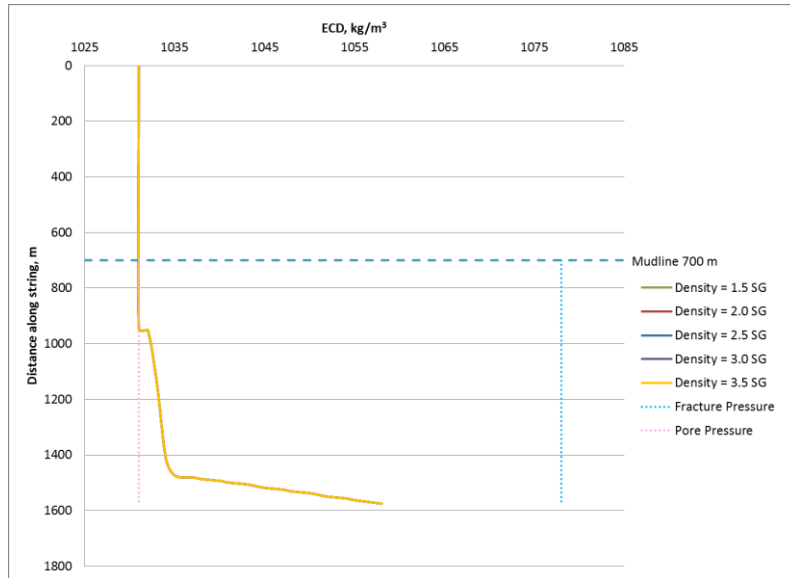


Fig. C. 1 – Changing cutting density did not result in a change in ECD for 875 mbsf using saltwater. The ECD does increase with increasing depth, but stay well within the operating window. The figure also shows a sharp increase in ECD over the BHA.

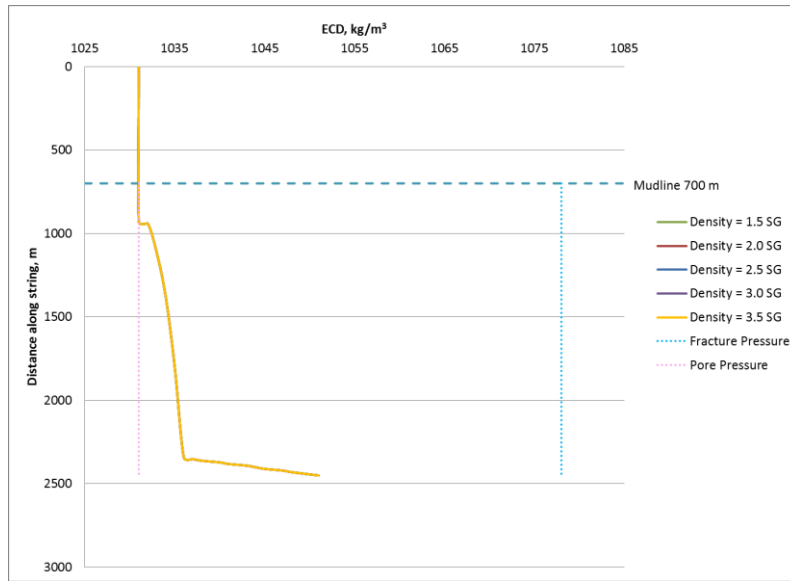


Fig. C. 2 – Changing cutting density did not result in a change in ECD for 1750 mbsf using saltwater. The ECD does increase with increasing depth, but stay well within the operating window. The figure also shows a sharp increase in ECD over the BHA.

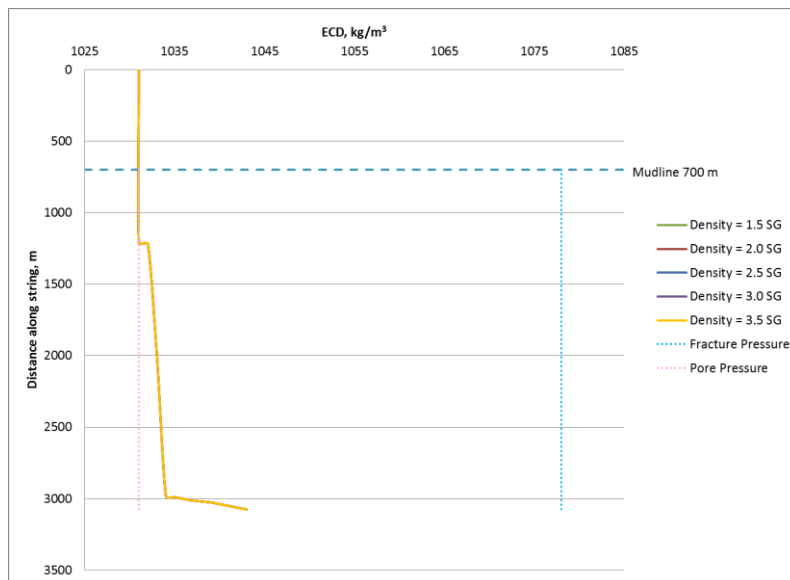


Fig. C. 3 – Changing cutting density did not result in a change in ECD for 2375 mbsf using saltwater. The ECD does increase with increasing depth, but stay well within the operating window. The figure also shows a sharp increase in ECD over the BHA.

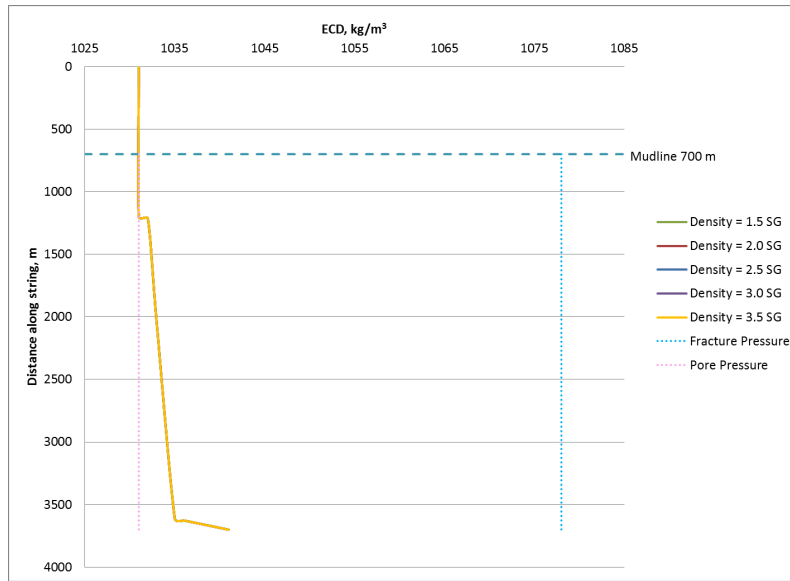


Fig. C. 4 – Changing cutting density did not result in a change in ECD for 3000 mbsf using saltwater. The ECD does increase with increasing depth, but stay well within the operating window. The figure also shows a sharp increase in ECD over the BHA.

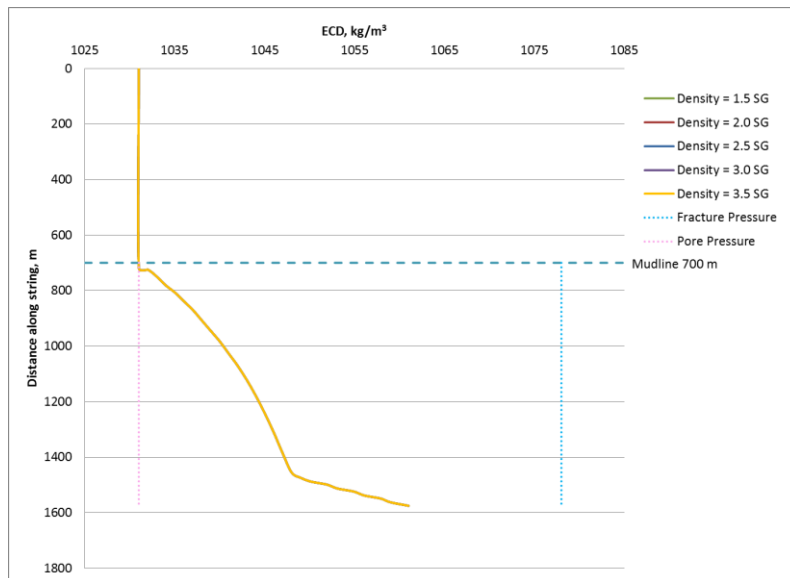


Fig. C. 5 – Changing cutting density did not result in a change in ECD for 875 mbsf using gel sweeps. The ECD does increase faster using gel sweeps than saltwater, but stays well within the operating window. The increase in ECD across the bit can also be seen using gel sweeps.

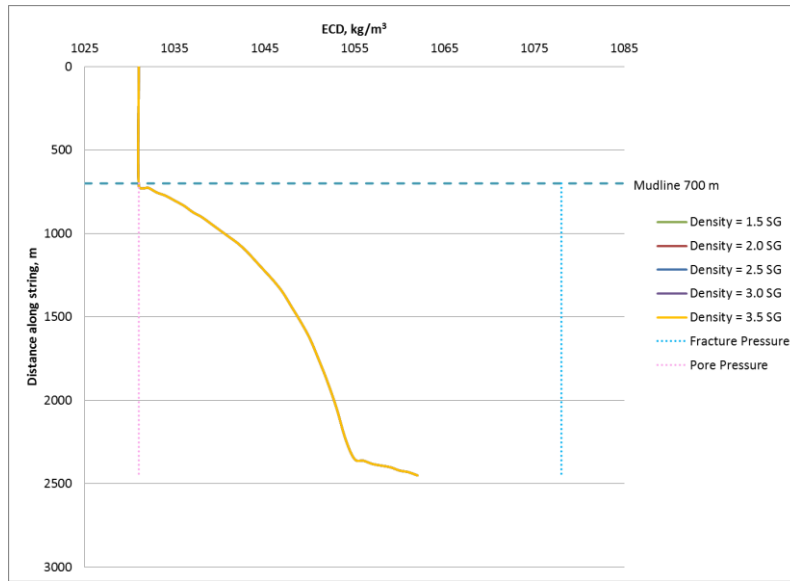


Fig. C. 6 – Changing cutting density did not result in a change in ECD for 1750 mbsf using gel sweeps. The ECD does increase faster using gel sweeps than saltwater, but stays well within the operating window. The increase in ECD across the bit can also be seen using gel sweeps.

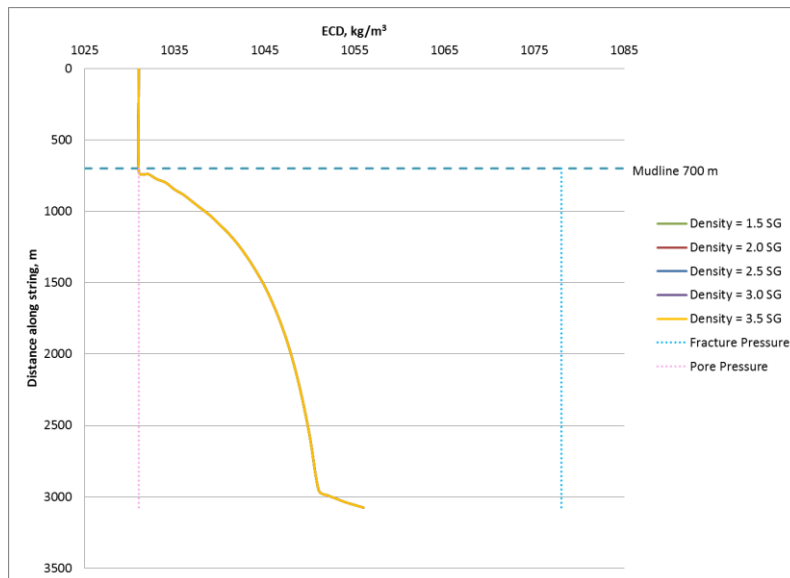


Fig. C. 7 – Changing cutting density did not result in a change in ECD for 2375 mbsf using gel sweeps. The ECD does increase faster using gel sweeps than saltwater, but stays well within the operating window. The increase in ECD across the bit can also be seen using gel sweeps.

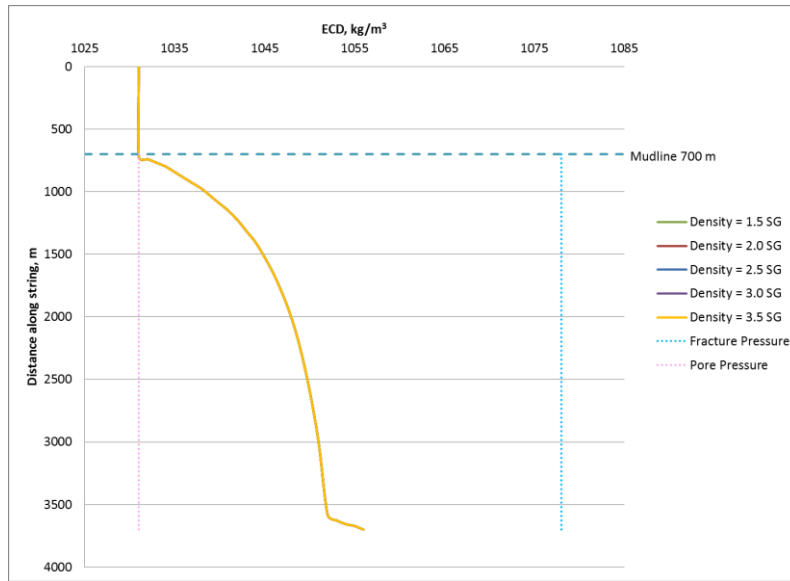


Fig. C. 8 – Changing cutting density did not result in a change in ECD for 3000 mbsf using gel sweeps. The ECD does increase faster using gel sweeps than saltwater, but stays well within the operating window. The increase in ECD across the bit can also be seen using gel sweeps.

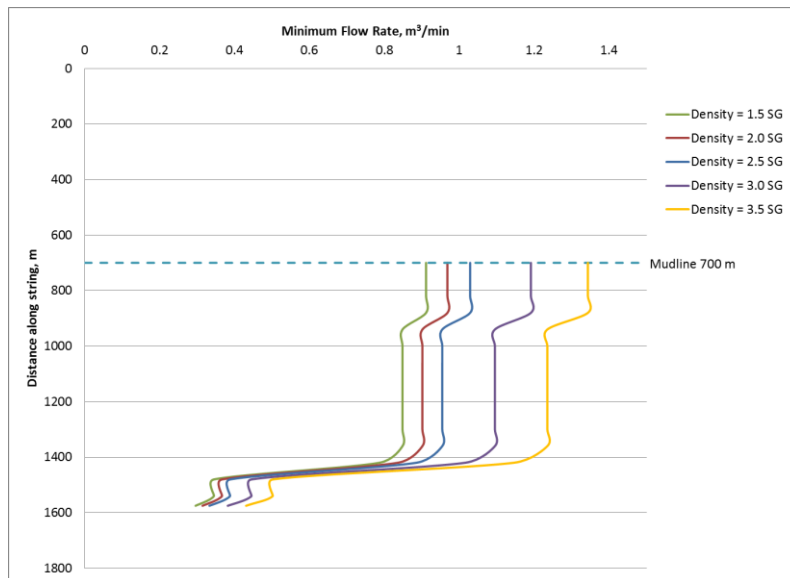


Fig. C. 9 – Shows that increasing the cutting density increases the minimum flow rate required using saltwater at 875 mbsf. The higher the specific gravity of the cutting density, the higher the flow rate required to prevent cutting concentration is. The flow rate required to clean the BHA remains nearly consistent for the different cutting densities.

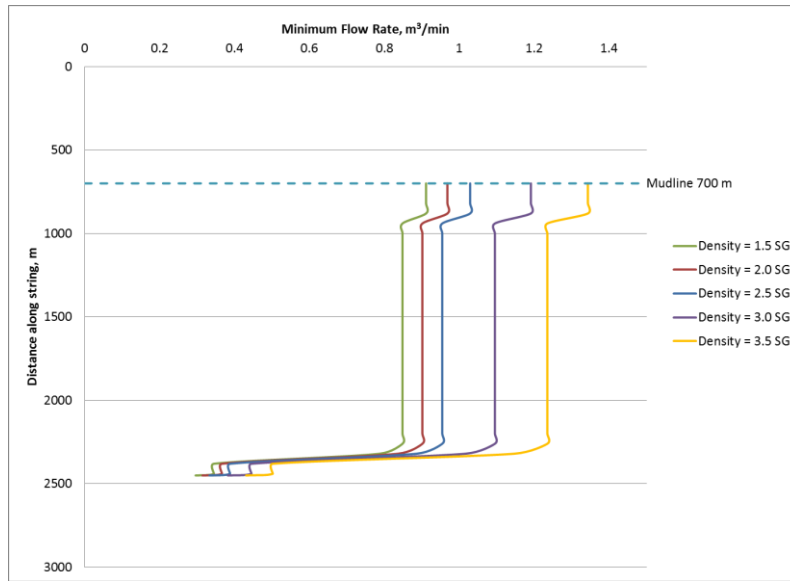


Fig. C. 10 – Shows that increasing the cutting density increases the minimum flow rate required using saltwater at 1750 mbsf. The higher the specific gravity of the cutting density, the higher the flow rate required to prevent cutting concentration is. The flow rate required to clean the BHA remains nearly consistent for the different cutting densities.

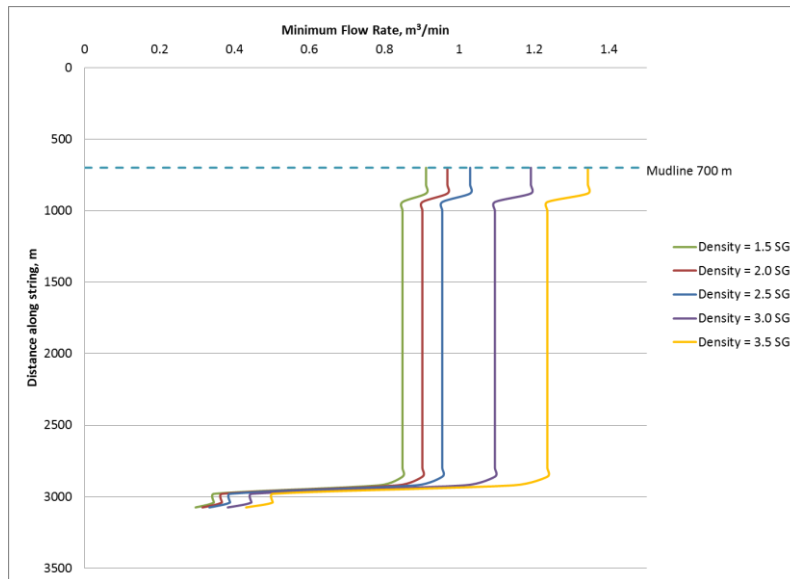


Fig. C. 11 – Shows that increasing the cutting density increases the minimum flow rate required using saltwater at 2375 mbsf. The higher the specific gravity of the cutting density, the higher the flow rate required to prevent cutting concentration is. The flow rate required to clean the BHA remains nearly consistent for the different cutting densities.

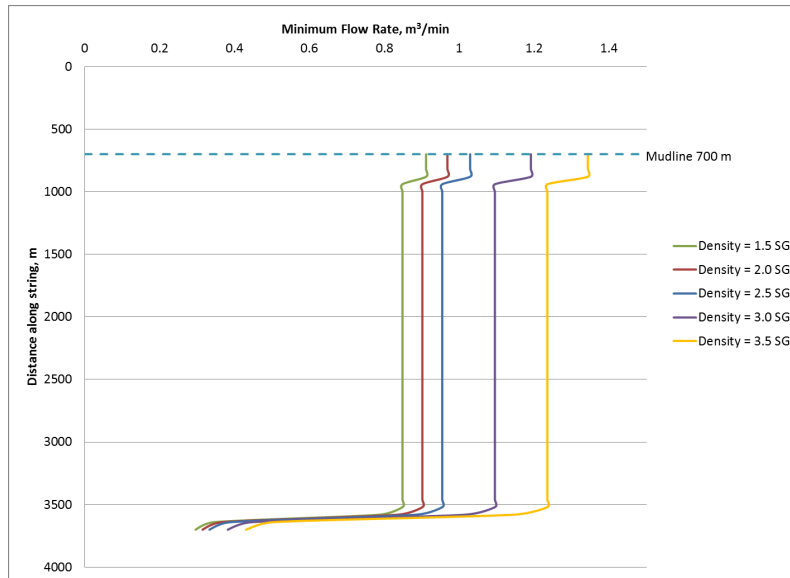


Fig. C. 12 – Shows that increasing the cutting density increases the minimum flow rate required using saltwater at 3000 mbsf. The higher the specific gravity of the cutting density, the higher the flow rate required to prevent cutting concentration is. The flow rate required to clean the BHA remains nearly consistent for the different cutting densities.

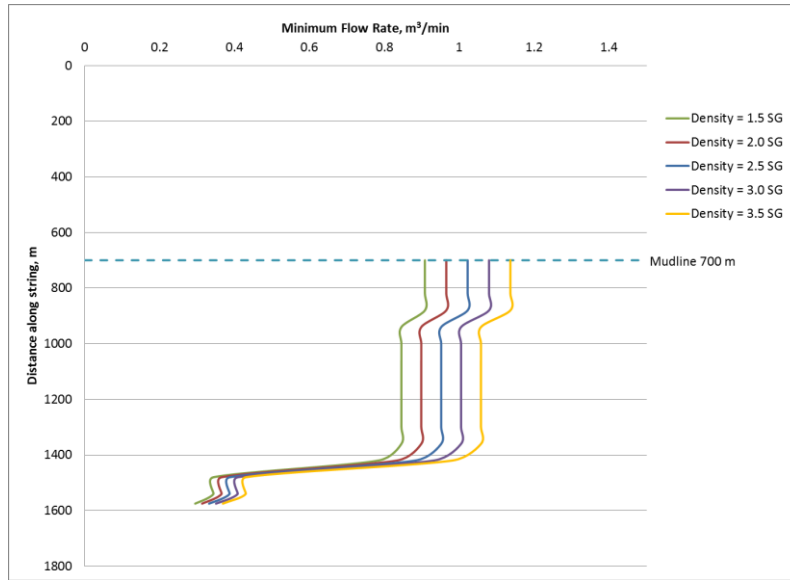


Fig. C. 13 – Shows that increasing the cutting density increases the minimum flow rate required using gel sweeps at 875 mbsf. The higher the specific gravity of the cutting density, the higher the flow rate required to prevent cutting concentration is. The flow rate required to clean the BHA remains nearly consistent for the different cutting densities. The minimum flow rate remains slightly lower for gel sweeps than saltwater at all depths.

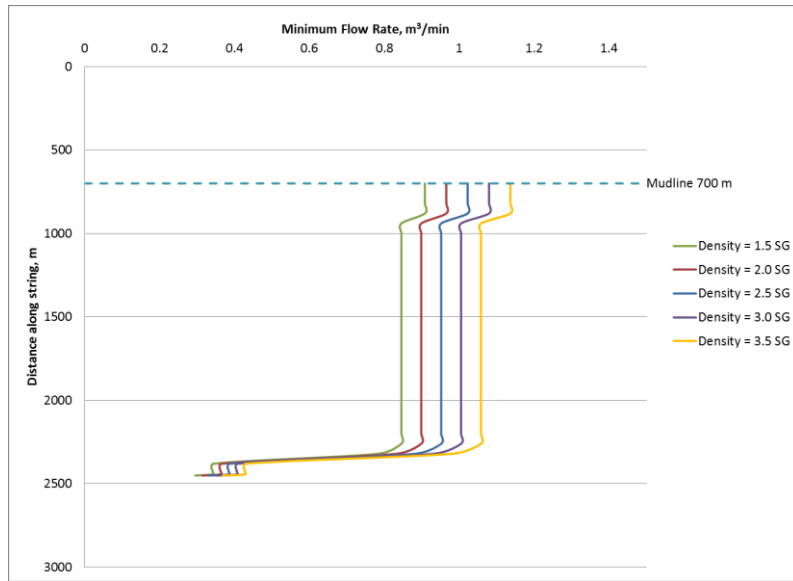


Fig. C. 14 – Shows that increasing the cutting density increases the minimum flow rate required using gel sweeps at 1750 mbsf. The higher the specific gravity of the cutting density, the higher the flow rate required to prevent cutting concentration is. The flow rate required to clean the BHA remains nearly consistent for the different cutting densities. The minimum flow rate remains slightly lower for gel sweeps than saltwater at all depths.

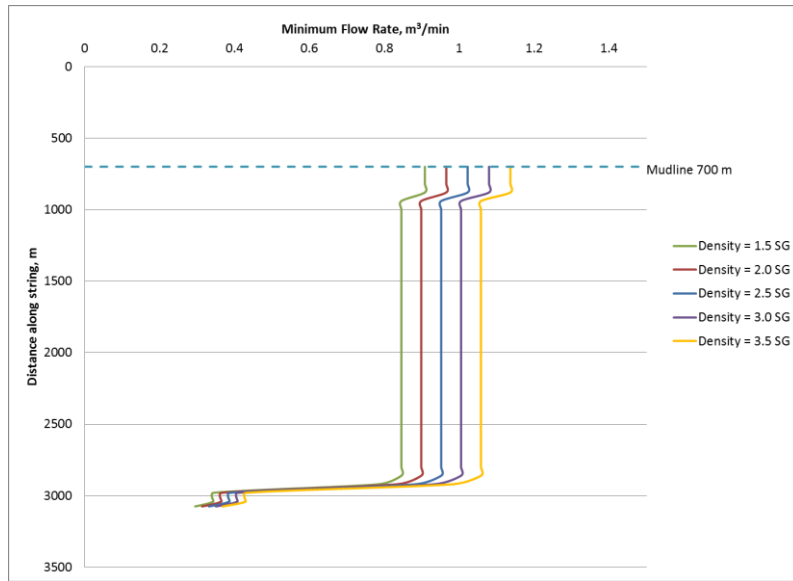


Fig. C. 15 – Shows that increasing the cutting density increases the minimum flow rate required using gel sweeps at 2375 mbsf. The higher the specific gravity of the cutting density, the higher the flow rate required to prevent cutting concentration is. The flow rate required to clean the BHA remains nearly consistent for the different cutting densities. The minimum flow rate remains slightly lower for gel sweeps than saltwater at all depths.

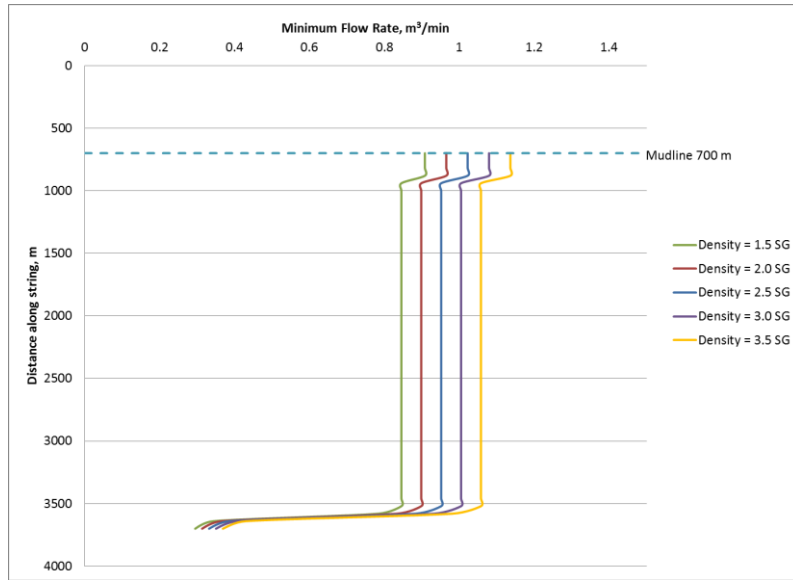


Fig. C. 16 – Shows that increasing the cutting density increases the minimum flow rate required using gel sweeps at 3000 mbsf. The higher the specific gravity of the cutting density, the higher the flow rate required to prevent cutting concentration is. The flow rate required to clean the BHA remains nearly consistent for the different cutting densities. The minimum flow rate remains slightly lower for gel sweeps than saltwater at all depths.

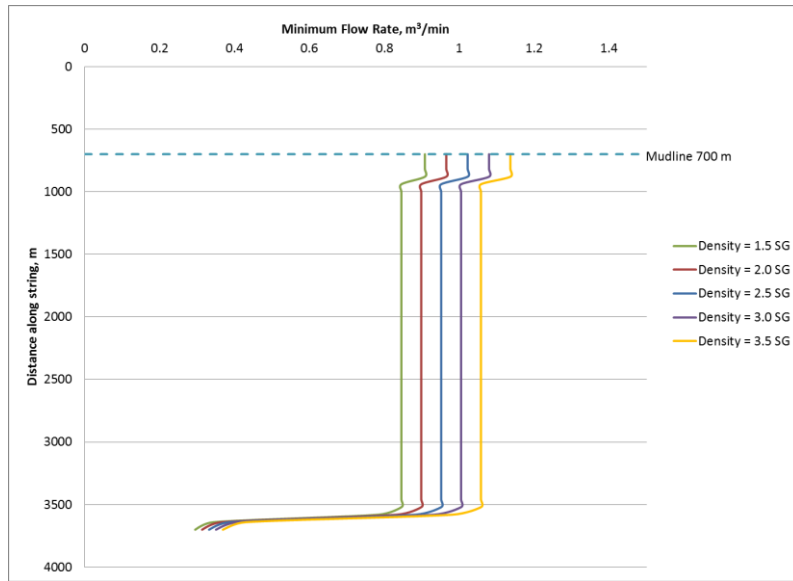


Fig. C. 17 – Shows that increasing the cutting density increases the amount of cutting percentage suspended in the annulus using saltwater at 875 mbsf. With increasing cutting densities, the particle velocity will increase which will suspend more cuttings in the annulus if the remaining variables are held constant.

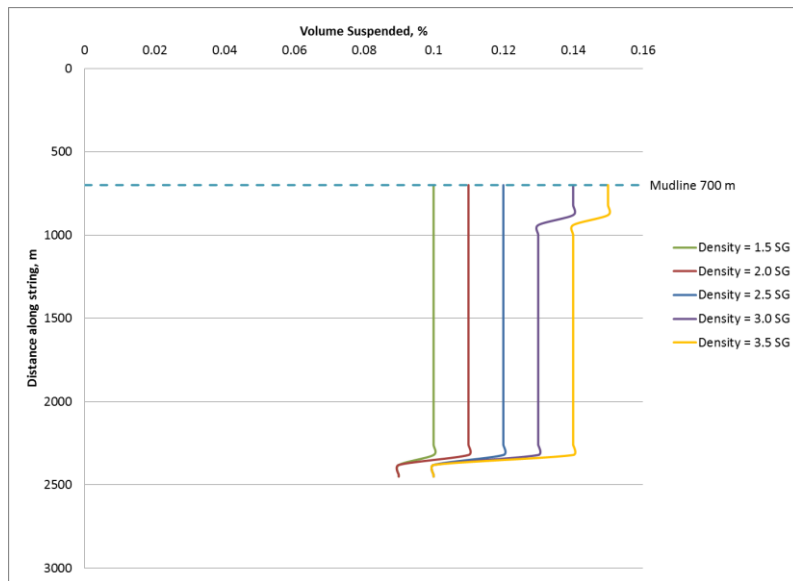


Fig. C. 18 – Shows that increasing the cutting density increases the amount of cutting percentage suspended in the annulus using saltwater at 1750 mbsf. With increasing cutting densities, the particle velocity will increase which will suspend more cuttings in the annulus if the remaining variables are held constant.

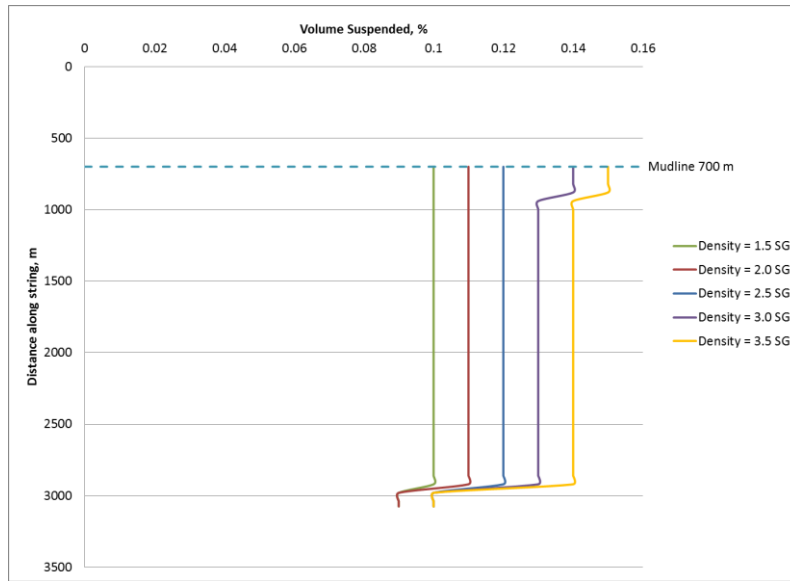


Fig. C. 19 – Shows that increasing the cutting density increases the amount of cutting percentage suspended in the annulus using saltwater at 2375 mbsf. With increasing cutting densities, the particle velocity will increase which will suspend more cuttings in the annulus if the remaining variables are held constant.

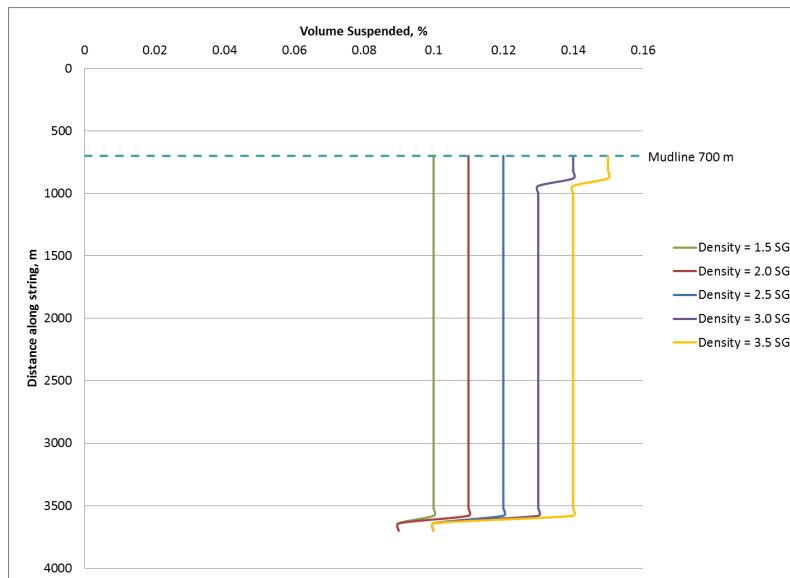


Fig. C. 20 – Shows that increasing the cutting density increases the amount of cutting percentage suspended in the annulus using saltwater at 3000 mbsf. With increasing cutting densities, the particle velocity will increase which will suspend more cuttings in the annulus if the remaining variables are held constant.

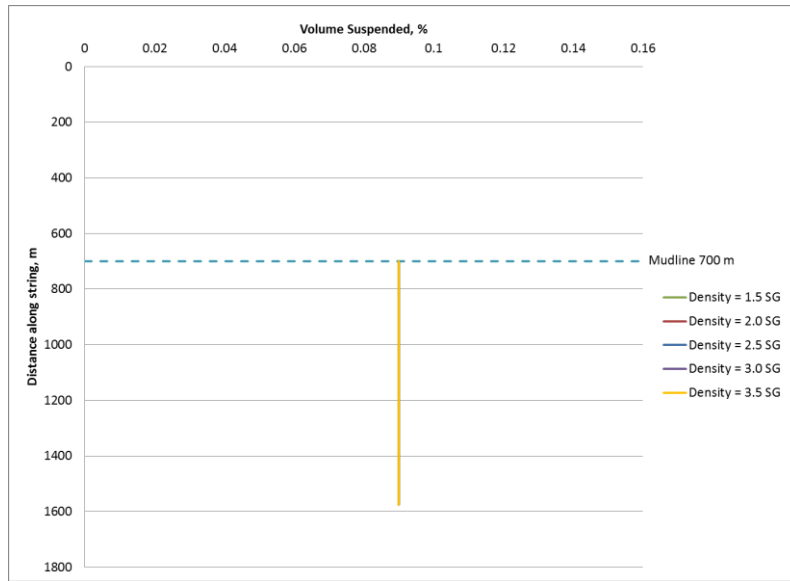


Fig. C. 21 – Shows that increasing the cutting density does not change the amount of cutting percentage suspended in the annulus using gel sweeps at 875 mbsf. The gel sweeps clean the hole just as efficiently with a specific gravity of 1.5 as a specific gravity of 3.5 with a constant volume suspended of 0.09%.

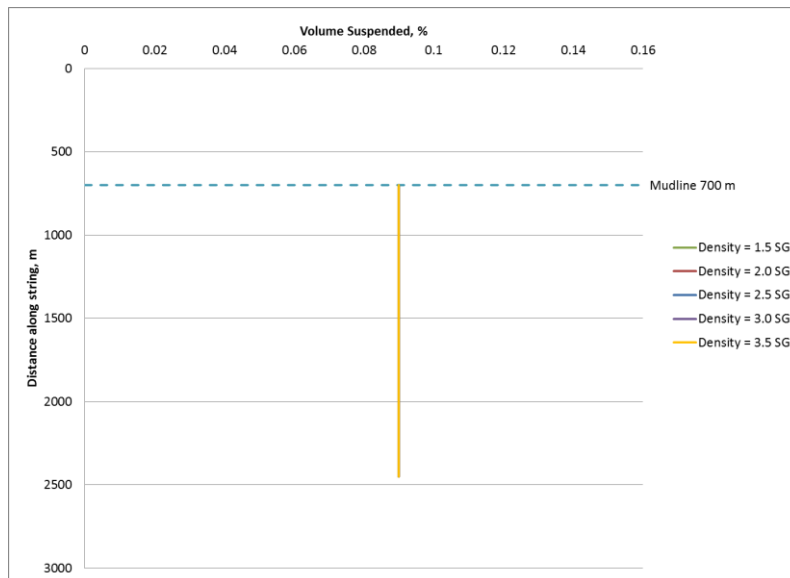


Fig. C. 22 – Shows that increasing the cutting density does not change the amount of cutting percentage suspended in the annulus using gel sweeps at 1750 mbsf. The gel sweeps clean the hole just as efficiently with a specific gravity of 1.5 as a specific gravity of 3.5 with a constant volume suspended of 0.09%.

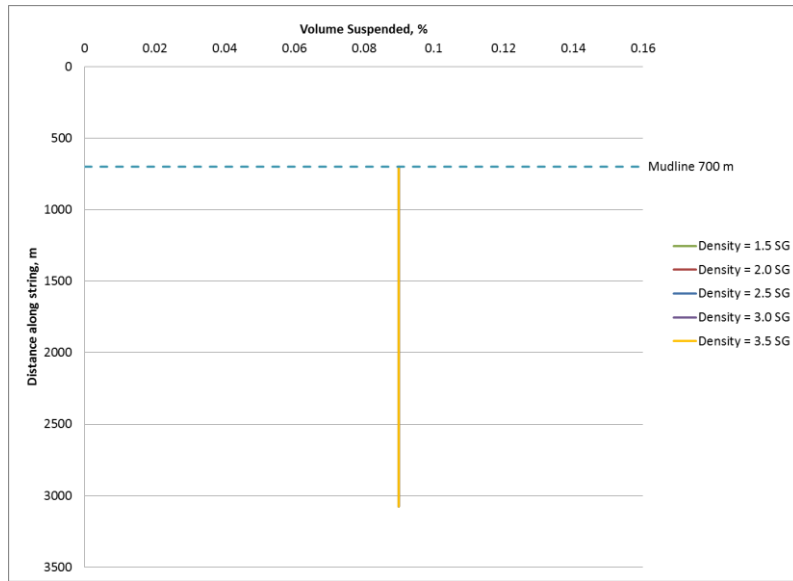


Fig. C. 23 – Shows that increasing the cutting density does not change the amount of cutting percentage suspended in the annulus using gel sweeps at 2375 mbsf. The gel sweeps clean the hole just as efficiently with a specific gravity of 1.5 as a specific gravity of 3.5 with a constant volume suspended of 0.09%.

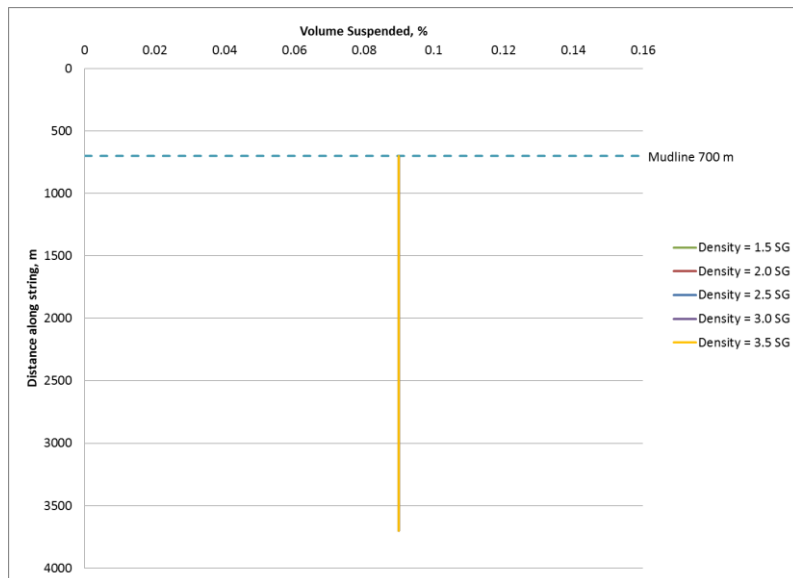


Fig. C. 24 – Shows that increasing the cutting density does not change the amount of cutting percentage suspended in the annulus using gel sweeps at 3000 mbsf. The gel sweeps clean the hole just as efficiently with a specific gravity of 1.5 as a specific gravity of 3.5 with a constant volume suspended of 0.09%.

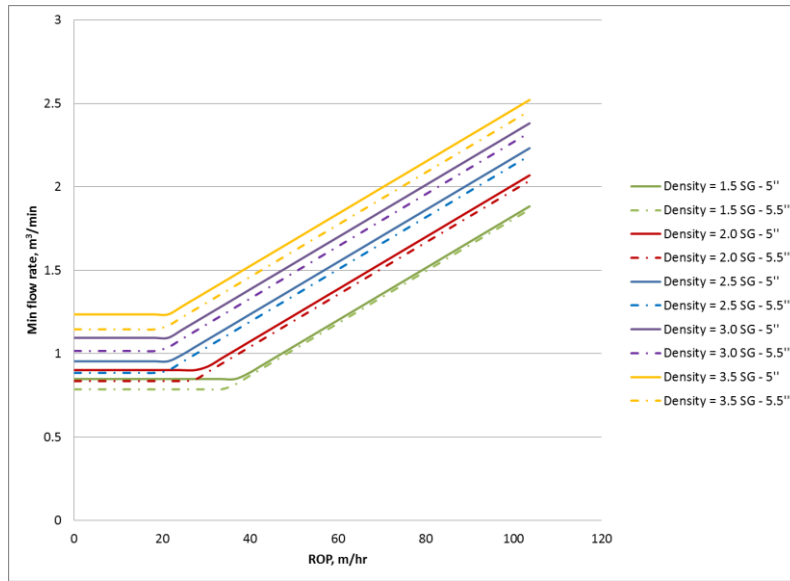


Fig. C. 25 – Shows that the increase in cutting density increases the minimum flow rate required for preventing cutting concentration buildup using saltwater at 875 mbsf. The 5" drill pipe requires a larger flow rate than 5 ½" drill pipe for all different cutting densities.

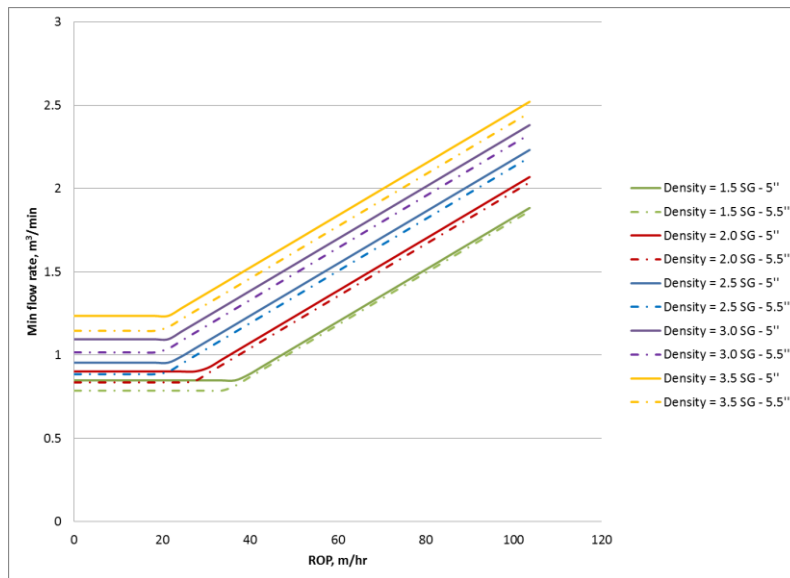


Fig. C. 26 – Shows that the increase in cutting density increases the minimum flow rate required for preventing cutting concentration buildup using saltwater at 1750 mbsf. The 5" drill pipe requires a larger flow rate than 5 ½" drill pipe for all different cutting densities.

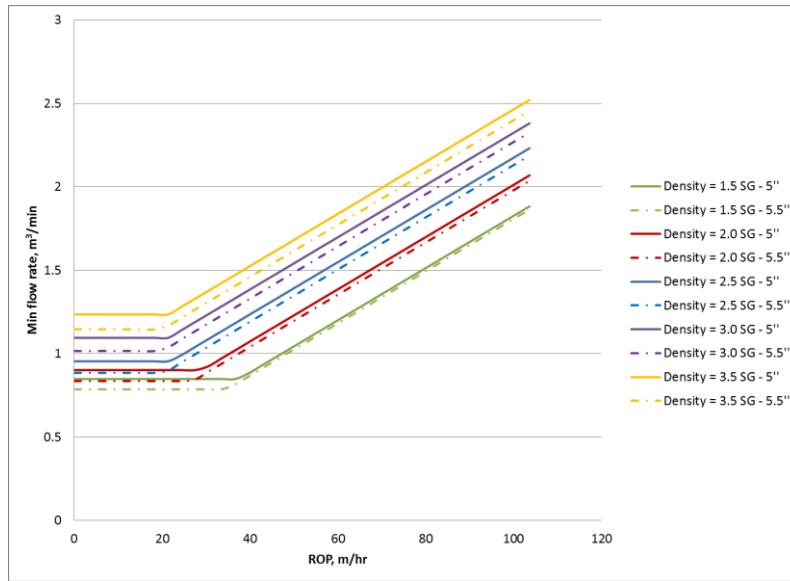


Fig. C. 27 – Shows that the increase in cutting density increases the minimum flow rate required for preventing cutting concentration buildup using saltwater at 2375 mbsf. The 5" drill pipe requires a larger flow rate than 5 1/2" drill pipe for all different cutting densities.

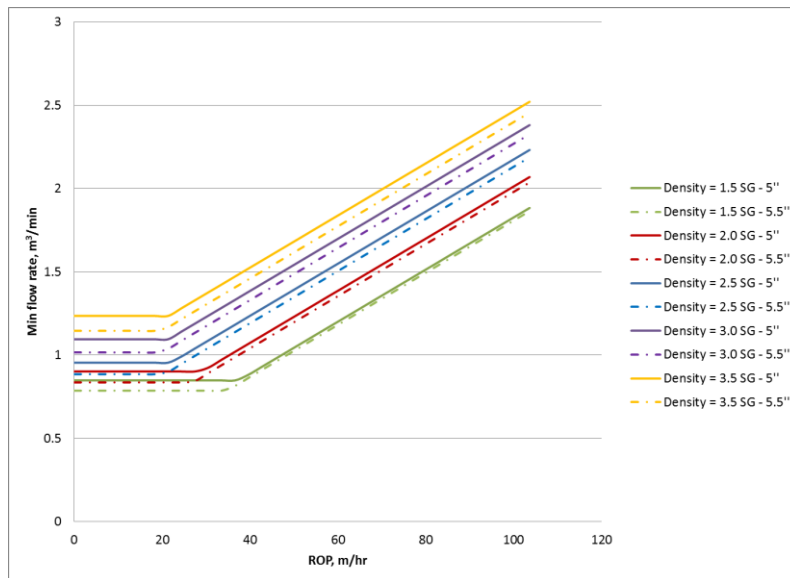


Fig. C. 28 – Shows that the increase in cutting density increases the minimum flow rate required for preventing cutting concentration buildup using saltwater at 3000 mbsf. The 5" drill pipe requires a larger flow rate than 5 1/2" drill pipe for all different cutting densities.

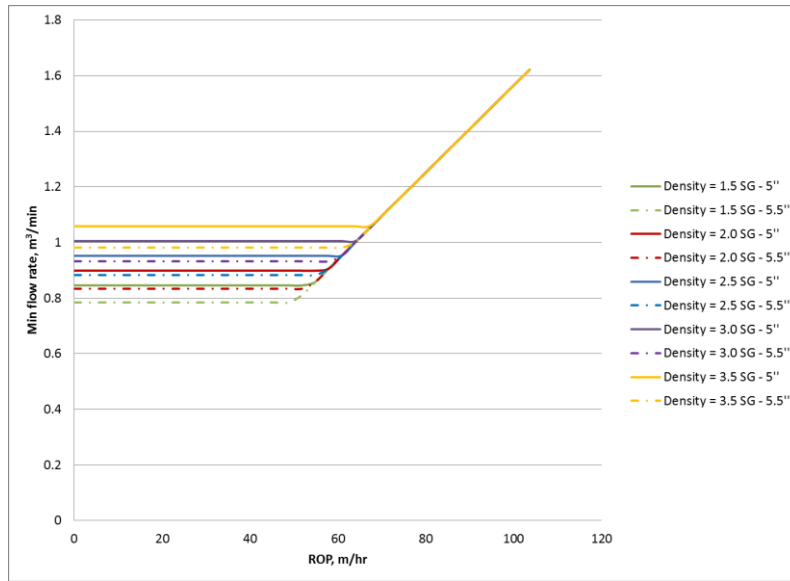


Fig. C. 29 – Shows that the increase in cutting density increases the minimum flow rate required for preventing cutting concentration buildup using gel sweeps at 875 mbsf. The 5" drill pipe requires a larger flow rate than 5 ½" drill pipe for ROP's between 0 and 50 m/hr for all different cutting densities. Past 50 m/hr, the flow rate required maintains constant for both drill pipe sizes.

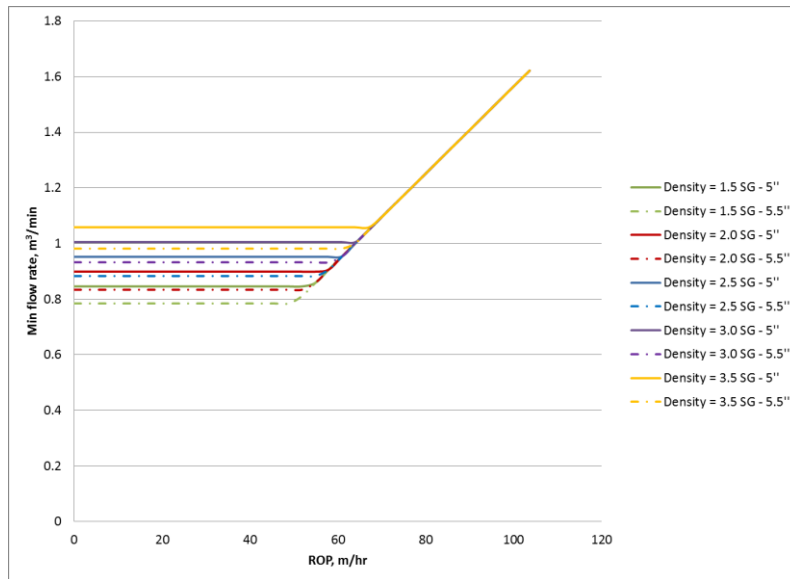


Fig. C. 30 – Shows that the increase in cutting density increases the minimum flow rate required for preventing cutting concentration buildup using gel sweeps at 1750 mbsf. The 5" drill pipe requires a larger flow rate than 5 ½" drill pipe for ROP's between 0 and 50 m/hr for all different cutting densities. Past 50 m/hr, the flow rate required maintains constant for both drill pipe sizes.

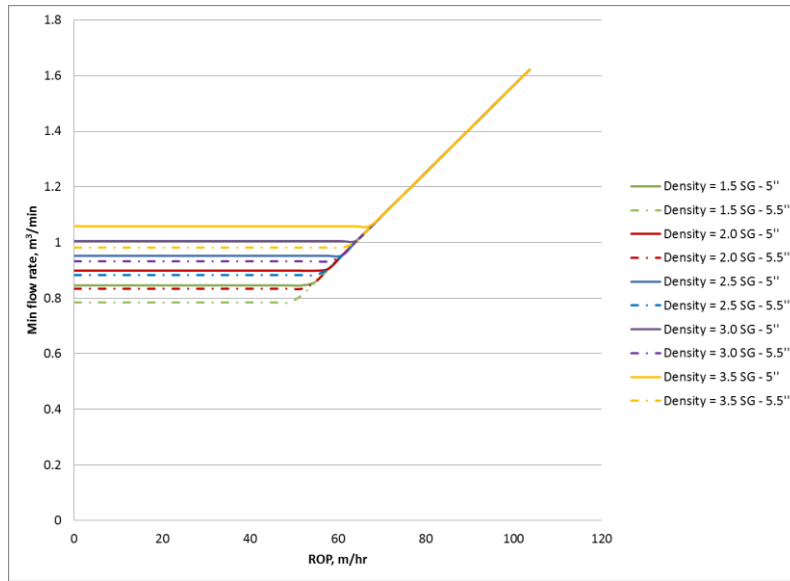


Fig. C. 31 – Shows that the increase in cutting density increases the minimum flow rate required for preventing cutting concentration buildup using gel sweeps at 2375 mbsf. The 5" drill pipe requires a larger flow rate than 5 ½" drill pipe for ROP's between 0 and 50 m/hr for all different cutting densities. Past 50 m/hr, the flow rate required maintains constant for both drill pipe sizes.

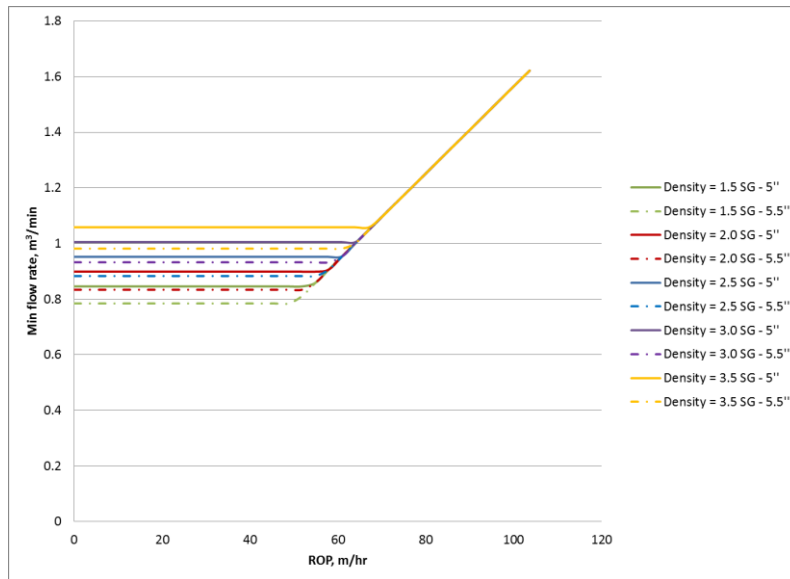


Fig. C. 32 – Shows that the increase in cutting density increases the minimum flow rate required for preventing cutting concentration buildup using gel sweeps at 3000 mbsf. The 5" drill pipe requires a larger flow rate than 5 ½" drill pipe for ROP's between 0 and 50 m/hr for all different cutting densities. Past 50 m/hr, the flow rate required maintains constant for both drill pipe sizes.

APPENDIX D

RESULTS FOR CHANGING CUTTING DIAMETER SIZE

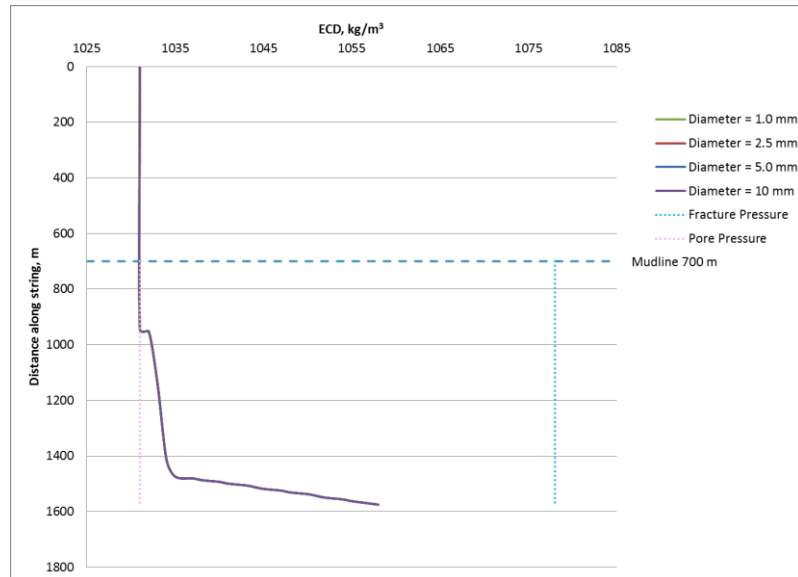


Fig. D.1 - Changing cutting size did not result in a change in ECD for 875 mbsf using saltwater. The ECD does increase with increasing depth, but stay well within the operating window. The figure also shows a sharp increase in ECD over the BHA.

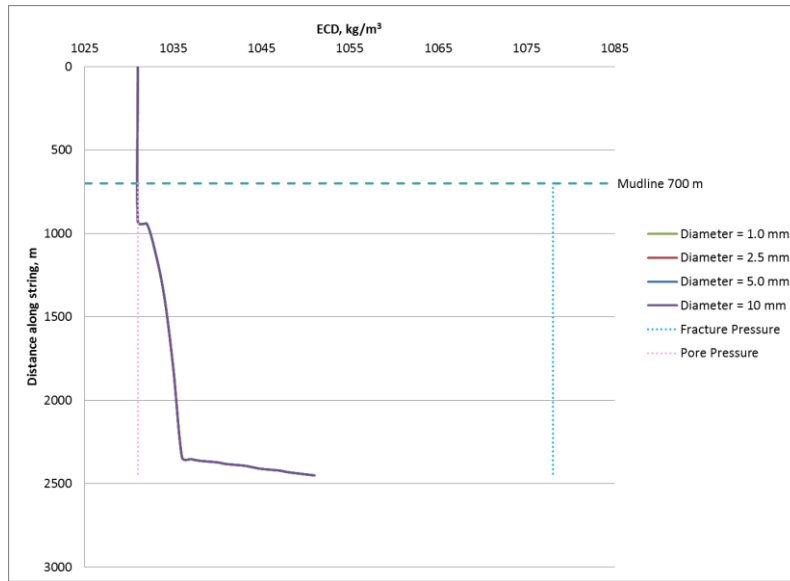


Fig. D.2 - Changing cutting size did not result in a change in ECD for 1750 mbsf using saltwater. The ECD does increase with increasing depth, but stay well within the operating window. The figure also shows a sharp increase in ECD over the BHA.

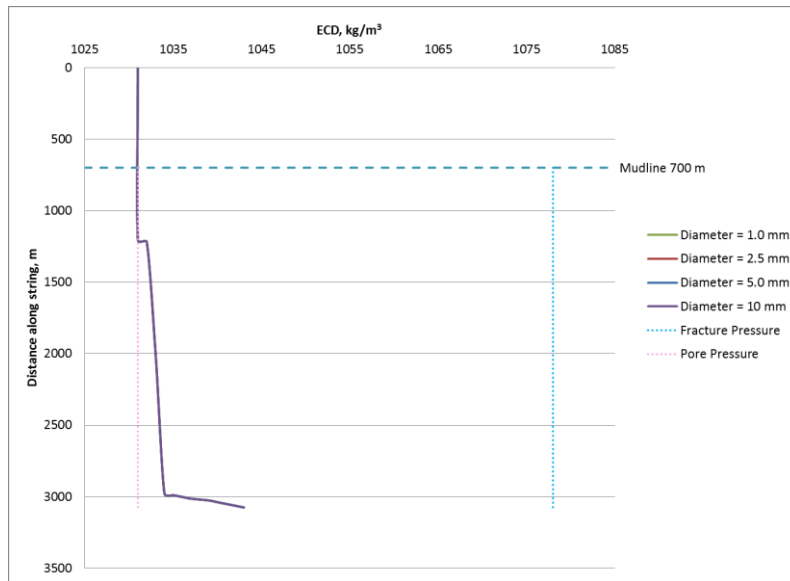


Fig. D.3 - Changing cutting size did not result in a change in ECD for 2375 mbsf using saltwater. The ECD does increase with increasing depth, but stay well within the operating window. The figure also shows a sharp increase in ECD over the BHA.

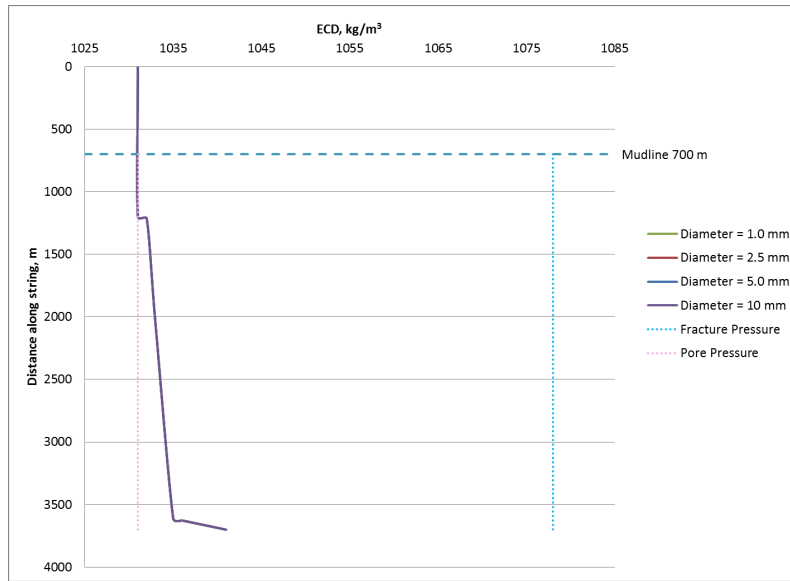


Fig. D.4 - Changing cutting size did not result in a change in ECD for 3000 mbsf using saltwater. The ECD does increase with increasing depth, but stay well within the operating window. The figure also shows a sharp increase in ECD over the BHA.

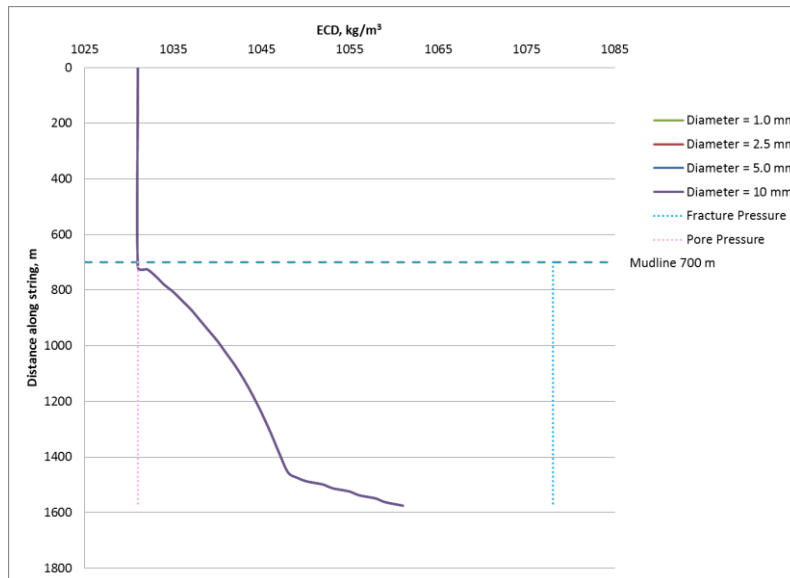


Fig. D.5 - Changing cutting size did not result in a change in ECD for 875 mbsf using gel sweeps. The ECD does increase faster using gel sweeps than saltwater, but stays well within the operating window. The increase in ECD across the bit can also be seen using gel sweeps.

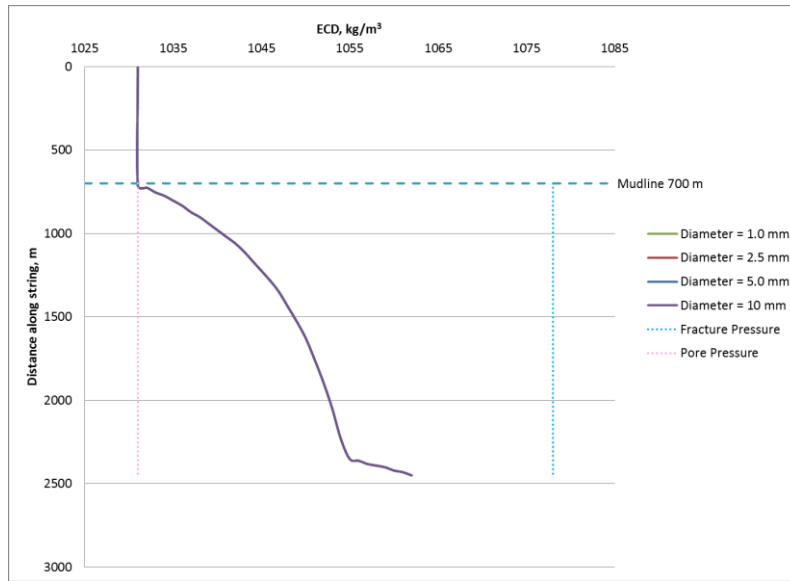


Fig. D.6 - Changing cutting size did not result in a change in ECD for 1750 mbsf using gel sweeps. The ECD does increase faster using gel sweeps than saltwater, but stays well within the operating window. The increase in ECD across the bit can also be seen using gel sweeps.

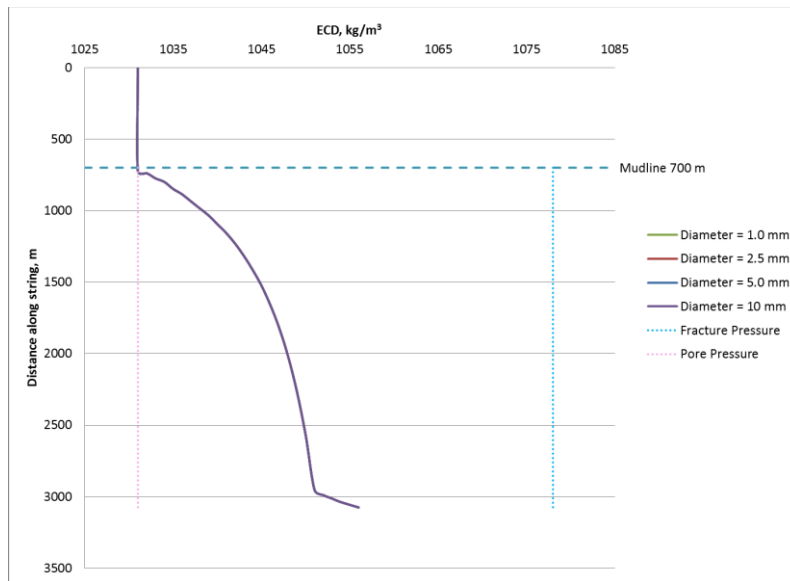


Fig. D.7 - Changing cutting size did not result in a change in ECD for 2375 mbsf using gel sweeps. The ECD does increase faster using gel sweeps than saltwater, but stays well within the operating window. The increase in ECD across the bit can also be seen using gel sweeps.

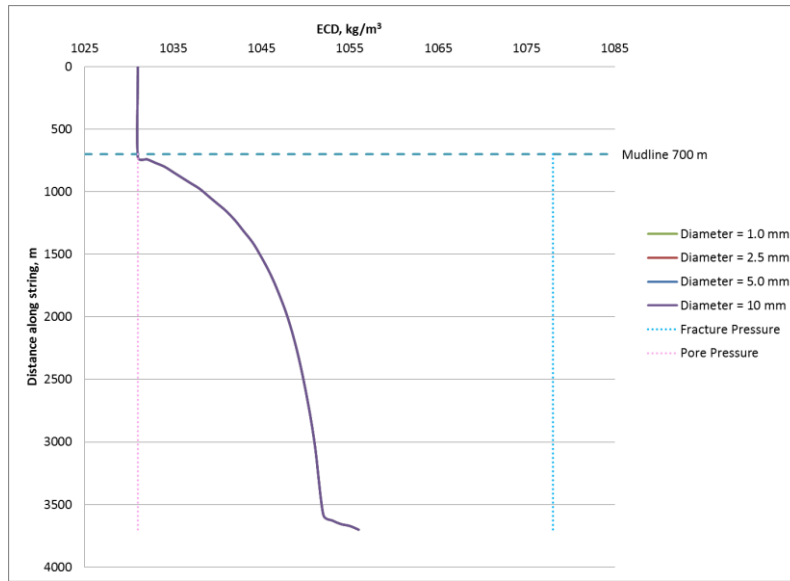


Fig. D.8 - Changing cutting size did not result in a change in ECD for 3000 mbsf using gel sweeps. The ECD does increase faster using gel sweeps than saltwater, but stays well within the operating window. The increase in ECD across the bit can also be seen using gel sweeps.

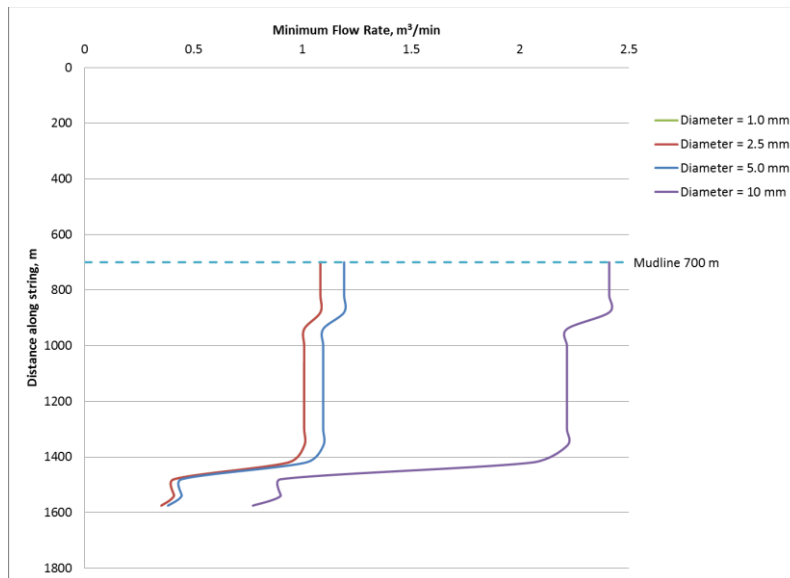


Fig. D.9 - Shows that “small” cutting diameter of 1-5 mm requires half the flow rate that the “large” cutting diameter of 10 mm requires to prevent cutting concentration buildup for saltwater at 875 mbsf. The flow rate required to clean the BHA is smaller for both the smaller and larger cutting diameters.

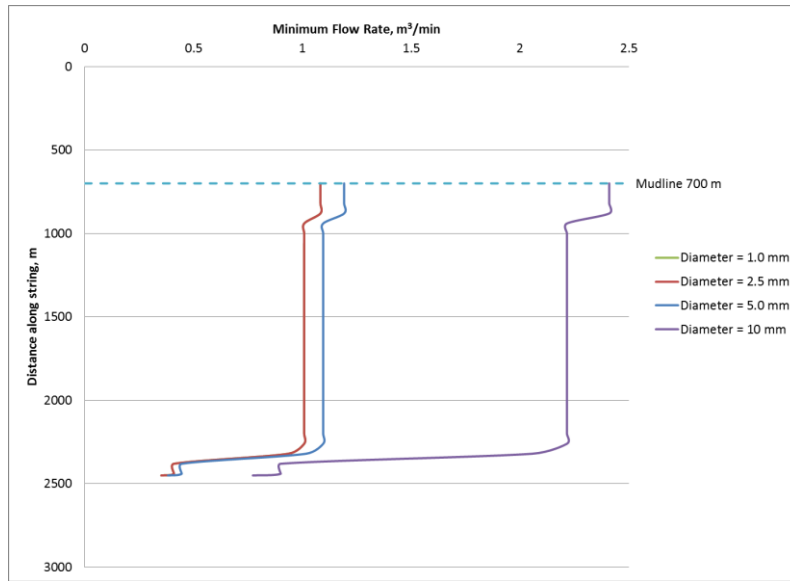


Fig. D.10 - Shows that “small” cutting diameter of 1-5 mm requires half the flow rate that the “large” cutting diameter of 10 mm requires to prevent cutting concentration buildup for saltwater at 1750 mbsf. The flow rate required to clean the BHA is smaller for both the smaller and larger cutting diameters.

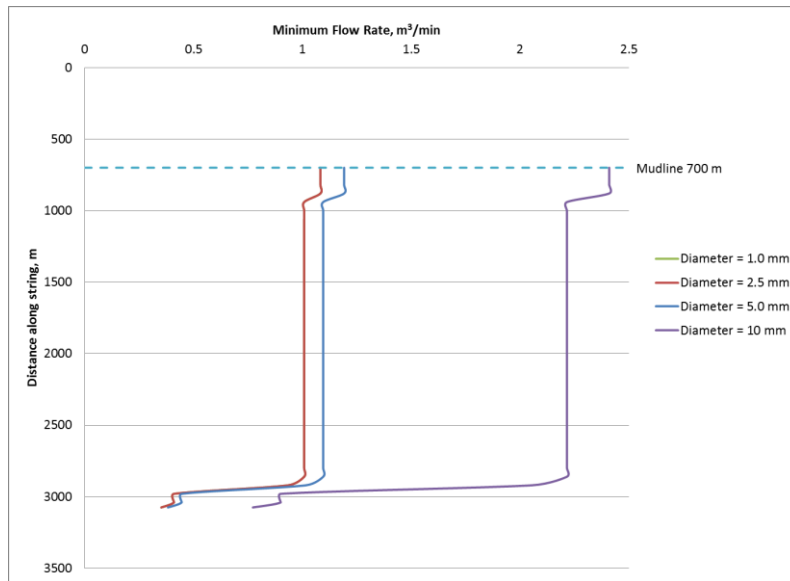


Fig. D.11 - Shows that “small” cutting diameter of 1-5 mm requires half the flow rate that the “large” cutting diameter of 10 mm requires to prevent cutting concentration buildup for saltwater at 2375 mbsf. The flow rate required to clean the BHA is smaller for both the smaller and larger cutting diameters.

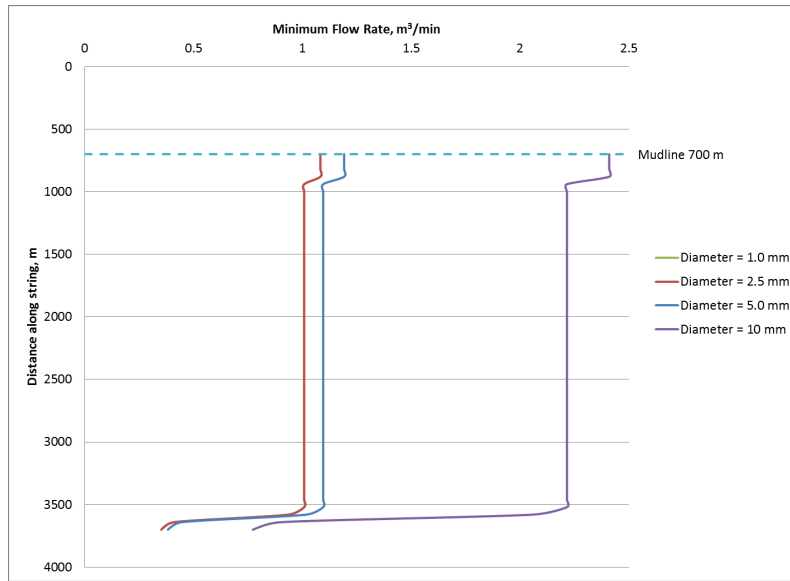


Fig. D.12 - Shows that “small” cutting diameter of 1-5 mm requires half the flow rate that the “large” cutting diameter of 10 mm requires to prevent cutting concentration buildup for saltwater at 3000 mbsf. The flow rate required to clean the BHA is smaller for both the smaller and larger cutting diameters.

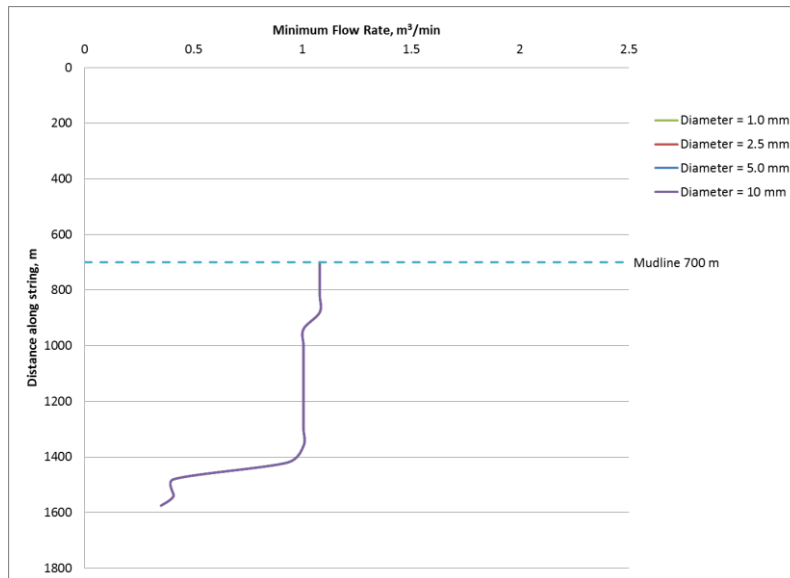


Fig. D.13 - Shows that gel sweeps for 875 mbsf require the same minimum flow rate to prevent cutting concentration for cutting sizes of 1 – 10 mm. The minimum flow rate required for gel sweeps is smaller than required for saltwater.

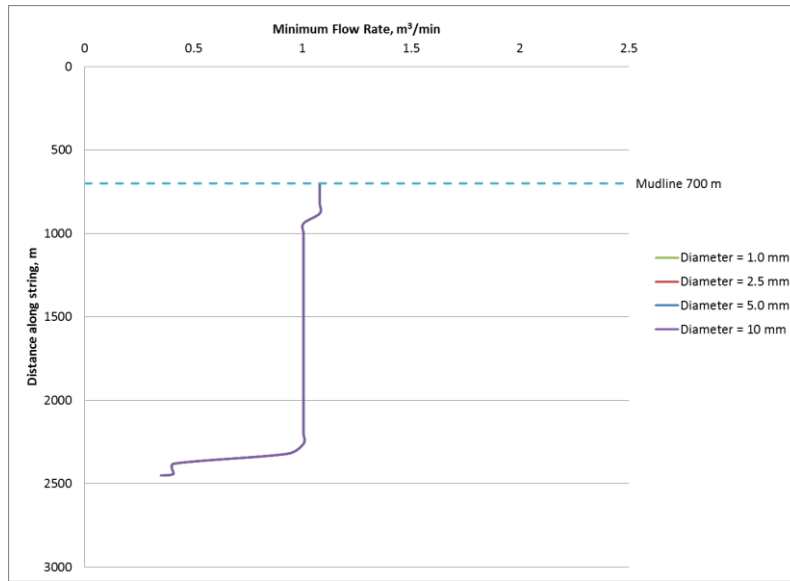


Fig. D.14 - Shows that gel sweeps for 1750 mbsf require the same minimum flow rate to prevent cutting concentration for cutting sizes of 1 – 10 mm. The minimum flow rate required for gel sweeps is smaller than required for saltwater.

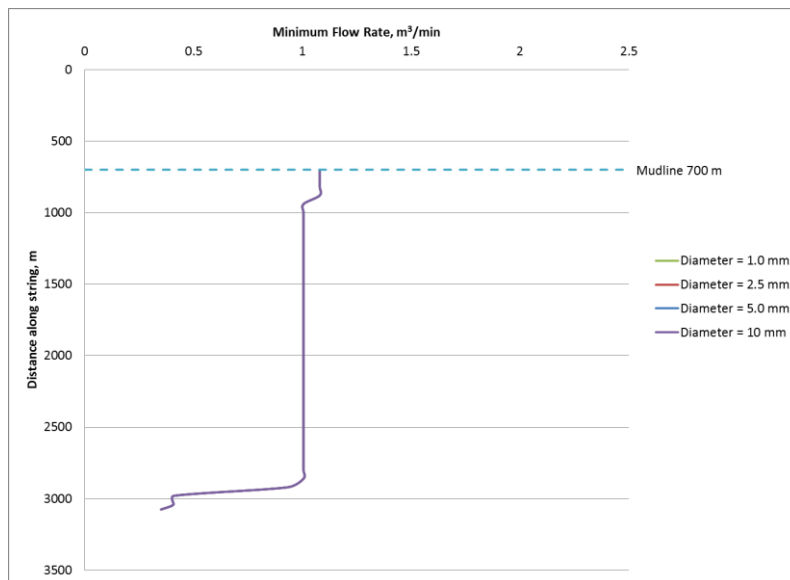


Fig. D.15 - Shows that gel sweeps for 2375 mbsf require the same minimum flow rate to prevent cutting concentration for cutting sizes of 1 – 10 mm. The minimum flow rate required for gel sweeps is smaller than required for saltwater.

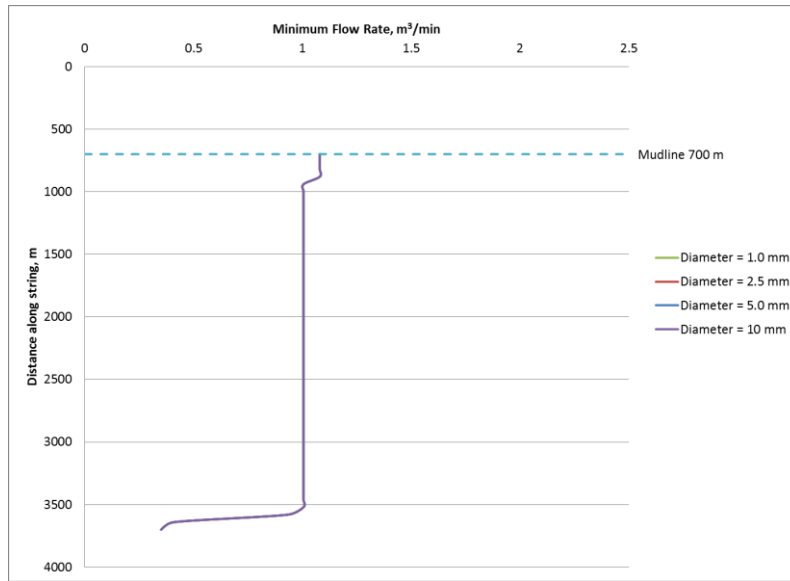


Fig. D.16 - Shows that gel sweeps for 3000 mbsf require the same minimum flow rate to prevent cutting concentration for cutting sizes of 1 – 10 mm. The minimum flow rate required for gel sweeps is smaller than required for saltwater.

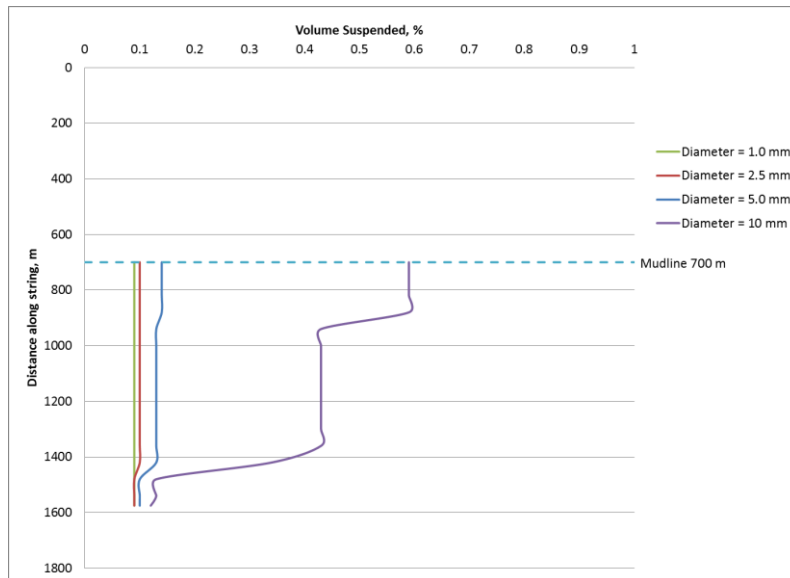


Fig. D.17 - Shows that increasing the cutting size increases the amount of cutting percentage suspended in the annulus when using seawater at 875 mbsf. With increasing cutting size, the particle slip velocity will increase which will suspend more cuttings in the annulus if the remaining variables are held constant.

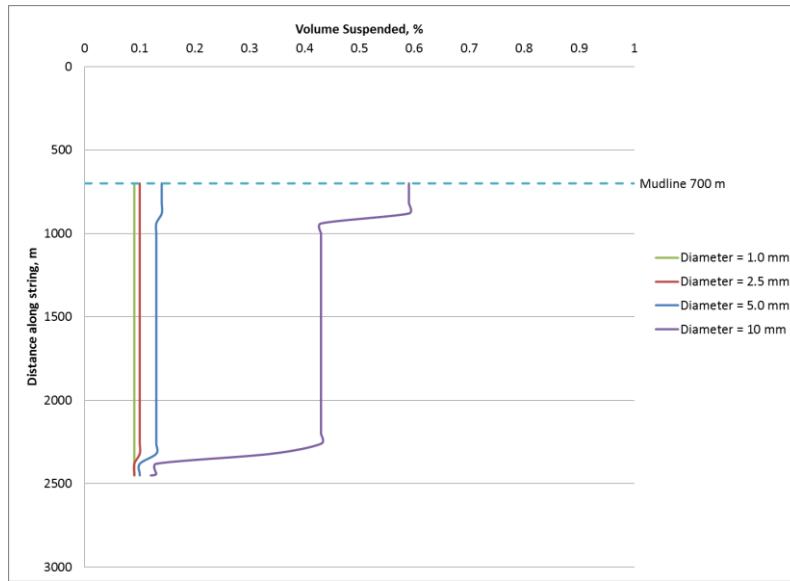


Fig. D.18 - Shows that increasing the cutting size increases the amount of cutting percentage suspended in the annulus when using seawater at 1750 mbsf. With increasing cutting size, the particle slip velocity will increase which will suspend more cuttings in the annulus if the remaining variables are held constant.

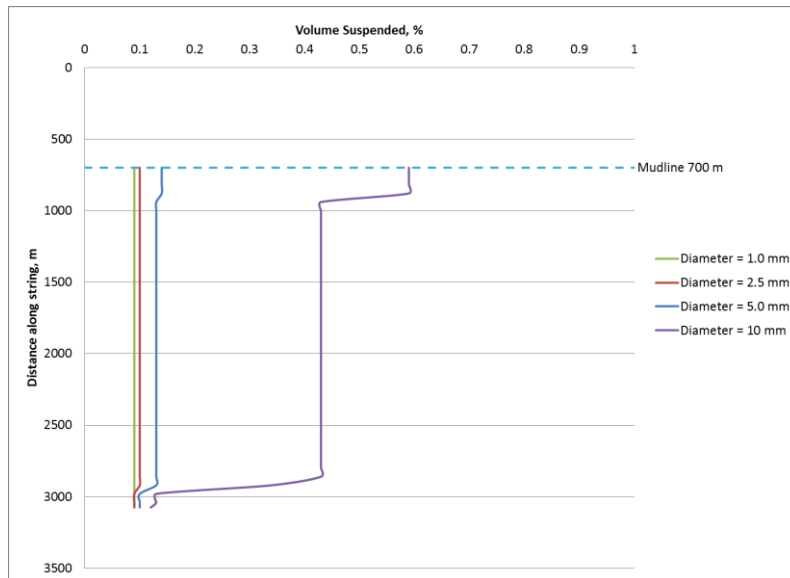


Fig. D.19 - Shows that increasing the cutting size increases the amount of cutting percentage suspended in the annulus when using seawater at 2375 mbsf. With increasing cutting size, the particle slip velocity will increase which will suspend more cuttings in the annulus if the remaining variables are held constant.

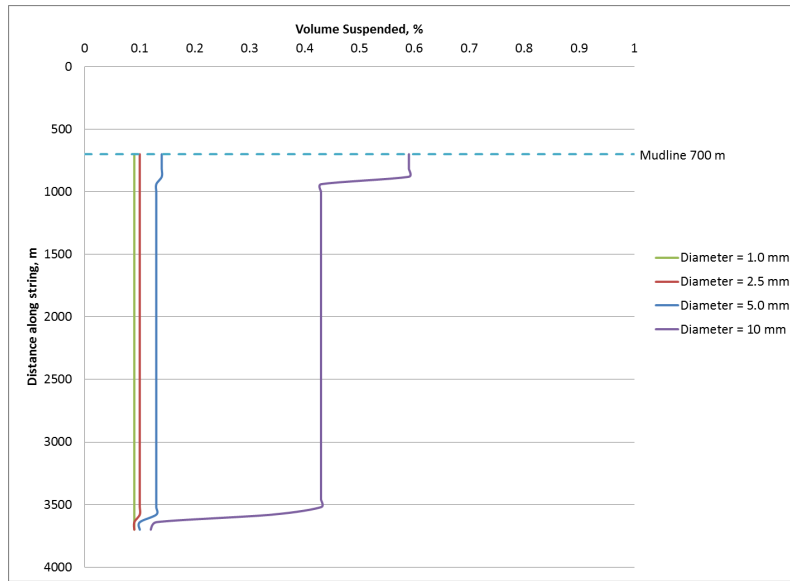


Fig. D.20 - Shows that increasing the cutting size increases the amount of cutting percentage suspended in the annulus when using seawater at 3000 mbsf. With increasing cutting size, the particle slip velocity will increase which will suspend more cuttings in the annulus if the remaining variables are held constant.

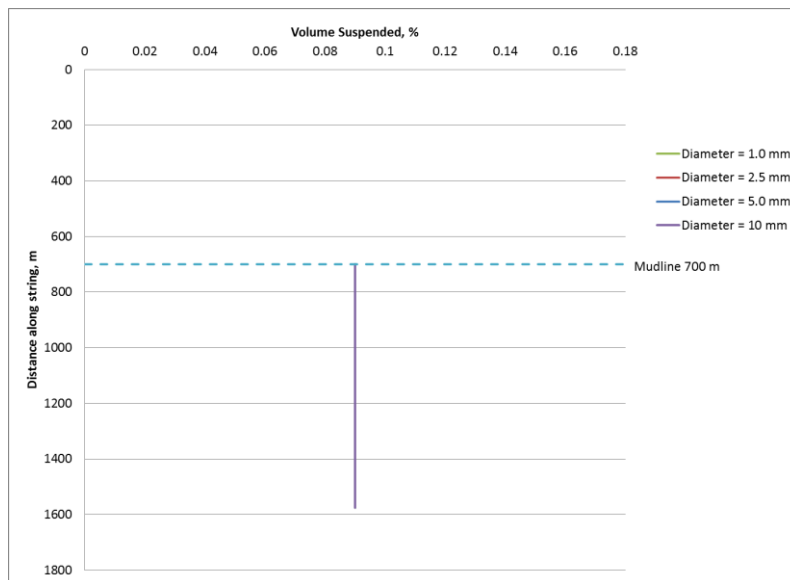


Fig. D.21 - Shows that increasing the cutting size does not change the amount of cutting percentage suspended in the annulus when using gel sweeps at 875 mbsf. With gel sweep as drilling fluid, the cutting volume suspended remains constant at 0.09%.

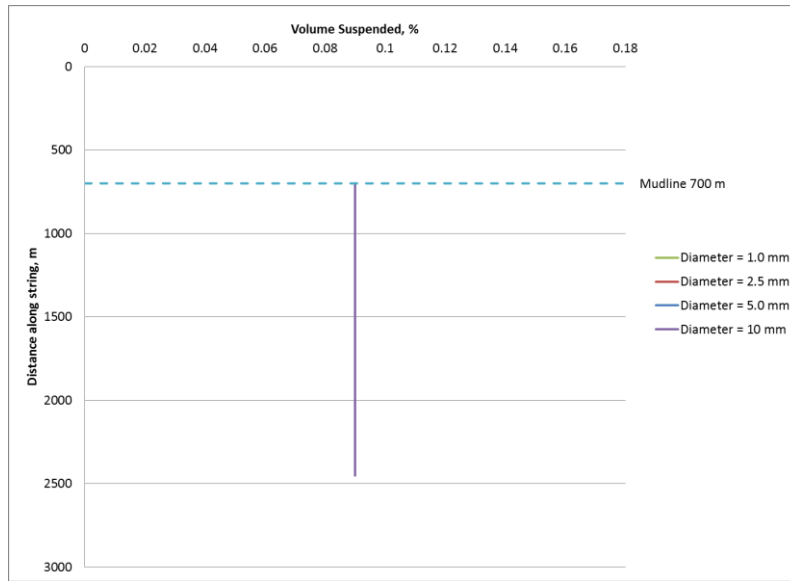


Fig. D.22 - Shows that increasing the cutting size does not change the amount of cutting percentage suspended in the annulus when using gel sweeps at 1750 mbsf. With gel sweep as drilling fluid, the cutting volume suspended remains constant at 0.09%.

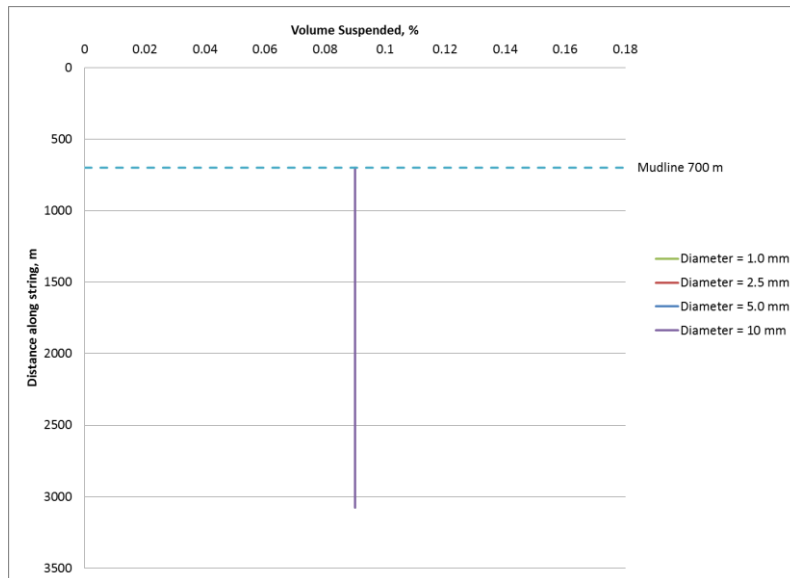


Fig. D.23 - Shows that increasing the cutting size does not change the amount of cutting percentage suspended in the annulus when using gel sweeps at 2375 mbsf. With gel sweep as drilling fluid, the cutting volume suspended remains constant at 0.09%.

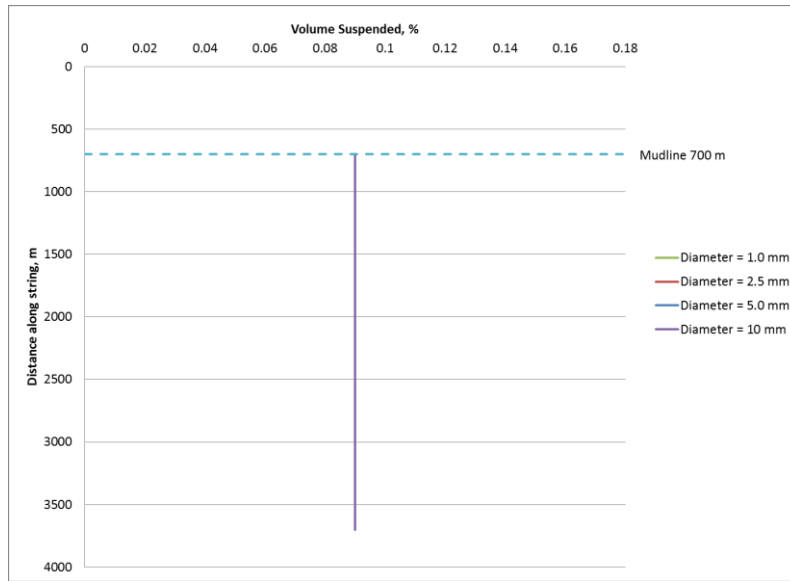


Fig. D.24 - Shows that increasing the cutting size does not change the amount of cutting percentage suspended in the annulus when using gel sweeps at 3000 mbsf. With gel sweep as drilling fluid, the cutting volume suspended remains constant at 0.09%.

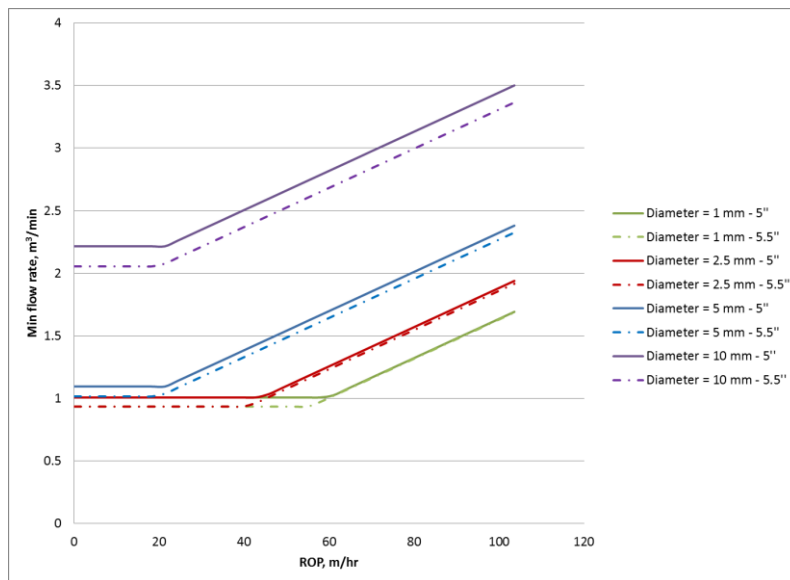


Fig. D.25 - Shows that increasing the cutting size requires a larger minimum flow rate to prevent cutting concentration buildup when using saltwater for 875 mbsf. The larger the diameter, the larger the difference is between flow rate required for 5'' and 5 1/2'' sized drill pipe. The 5'' drill pipe requires larger flow rate than 5 1/2'' drill pipe for all diameters except 1 mm cutting size.

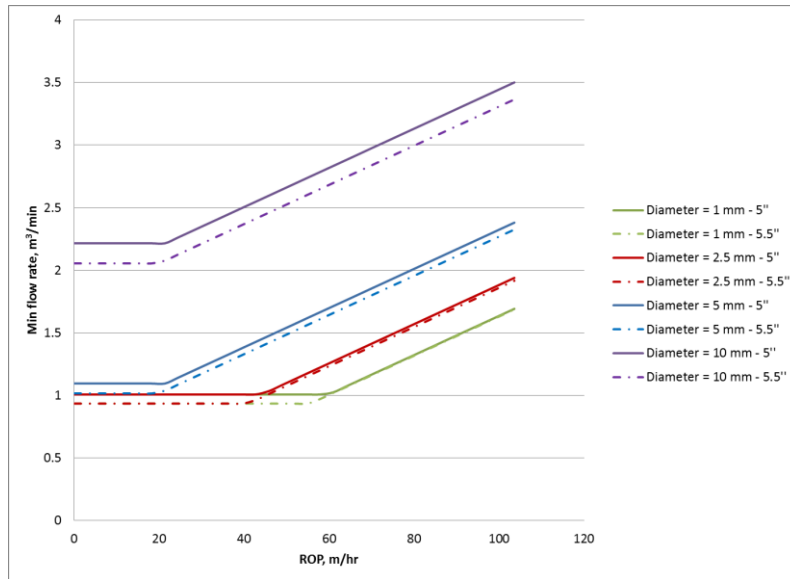


Fig. D.26 - Shows that increasing the cutting size requires a larger minimum flow rate to prevent cutting concentration buildup when using saltwater for 1750 mbsf. The larger the diameter, the larger the difference is between flow rate required for 5" and 5 ½" sized drill pipe. The 5" drill pipe requires larger flow rate than 5 ½" drill pipe for all diameters except 1 mm cutting size.

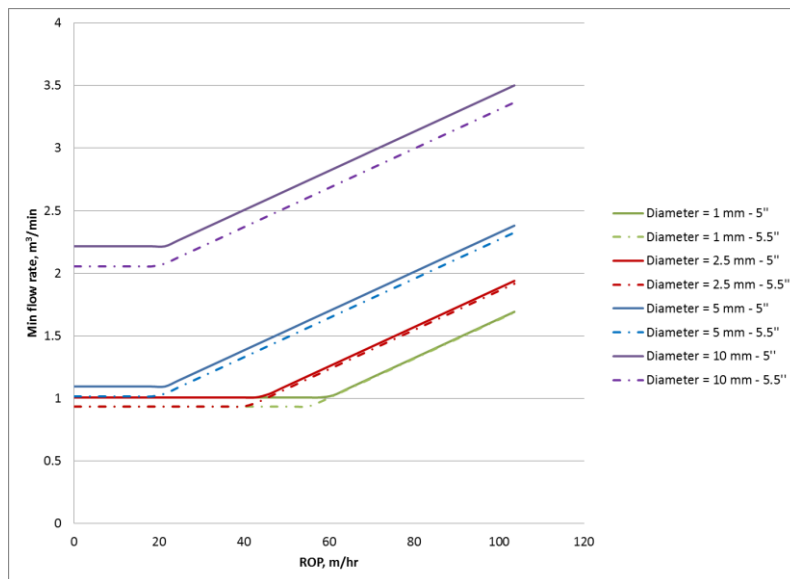


Fig. D.27 - Shows that increasing the cutting size requires a larger minimum flow rate to prevent cutting concentration buildup when using saltwater for 2375 mbsf. The larger the diameter, the larger the difference is between flow rate required for 5" and 5 ½" sized drill pipe. The 5" drill pipe requires larger flow rate than 5 ½" drill pipe for all diameters except 1 mm cutting size.

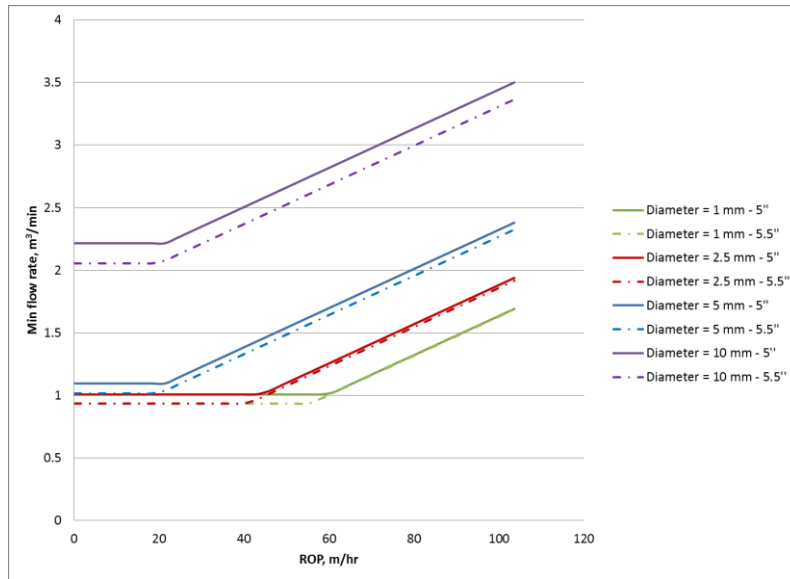


Fig. D.28 - Shows that increasing the cutting size requires a larger minimum flow rate to prevent cutting concentration buildup when using saltwater for 3000 mbsf. The larger the diameter, the larger the difference is between flow rate required for 5'' and 5 1/2'' sized drill pipe. The 5'' drill pipe requires larger flow rate than 5 1/2'' drill pipe for all diameters except 1 mm cutting size.

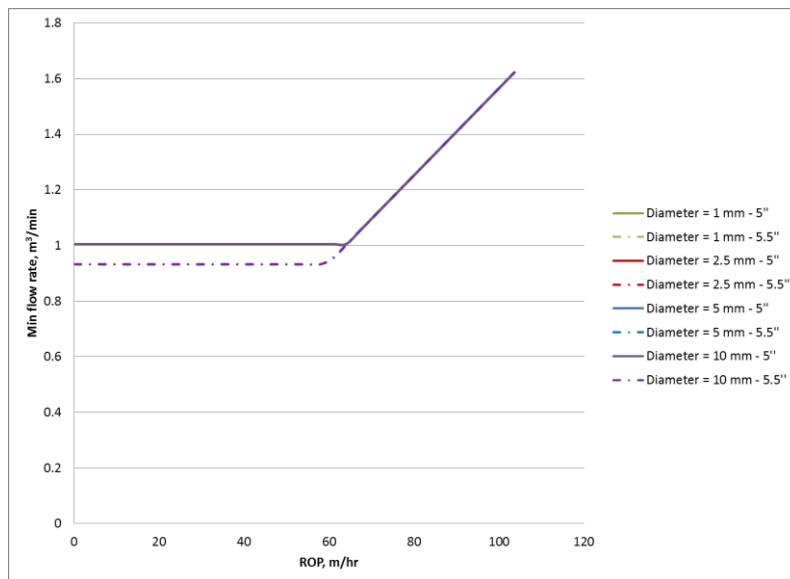


Fig. D.29 - The minimum flow rate required to clean the hole remains constant for ROP's up to 60 m/hr, but then increase linearly for gel sweeps at 875 mbsf. The 5'' drill pipe require a higher flow rate for ROP's between 0 and 60 m/hr, but past 60 m/hr the flow rate for 5'' and 5 1/2'' drill pipe remain the same using gel sweeps.

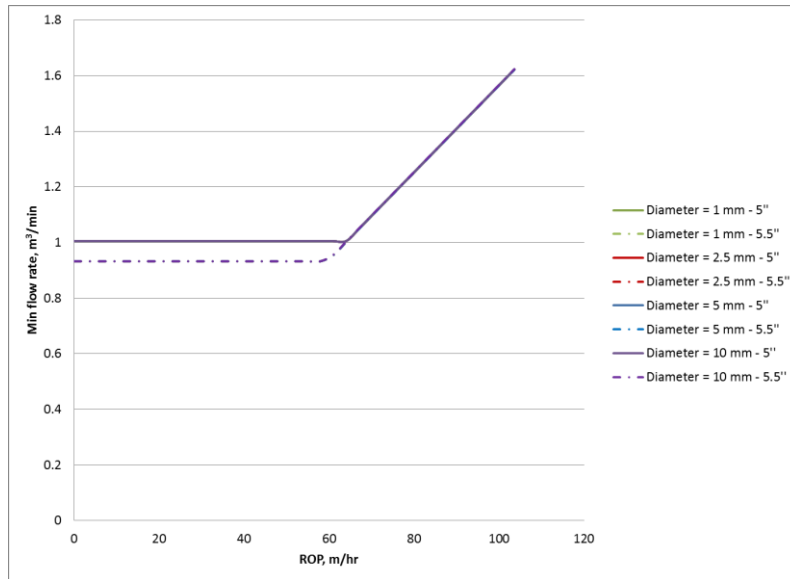


Fig. D.30 - The minimum flow rate required to clean the hole remains constant for ROP's up to 60 m/hr, but then increase linearly for gel sweeps at 1750 mbsf. The 5'' drill pipe require a higher flow rate for ROP's between 0 and 60 m/hr, but past 60 m/hr the flow rate for 5'' and 5 ½'' drill pipe remain the same using gel sweeps.

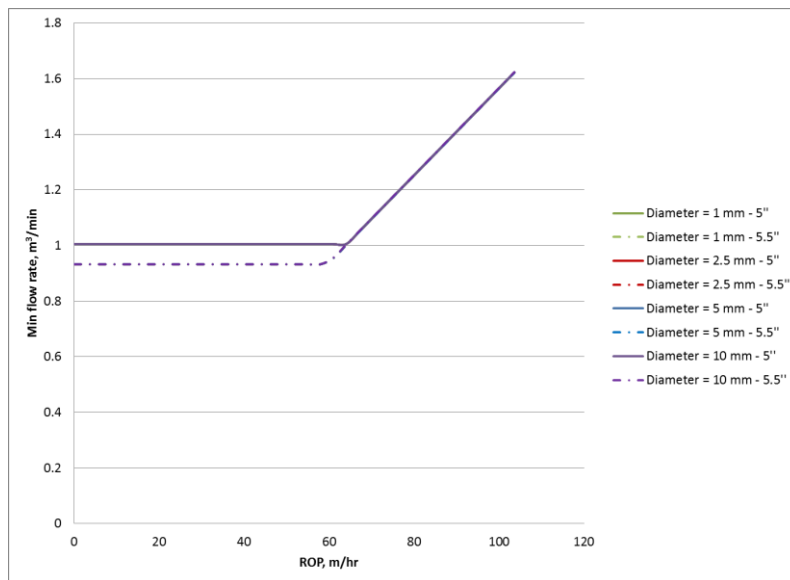


Fig. D.31 - The minimum flow rate required to clean the hole remains constant for ROP's up to 60 m/hr, but then increase linearly for gel sweeps at 2375 mbsf. The 5'' drill pipe require a higher flow rate for ROP's between 0 and 60 m/hr, but past 60 m/hr the flow rate for 5'' and 5 ½'' drill pipe remain the same using gel sweeps.

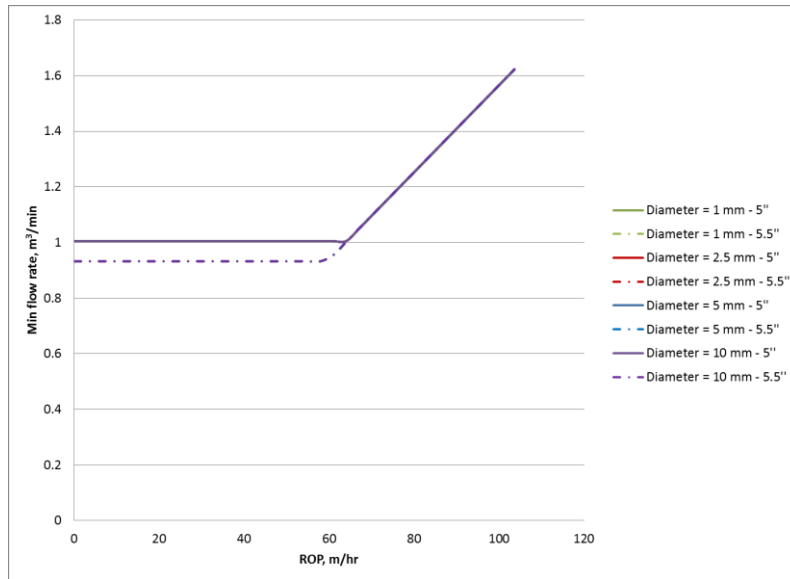


Fig. D.32 - The minimum flow rate required to clean the hole remains constant for ROP's up to 60 m/hr, but then increase linearly for gel sweeps at 3000 mbsf. The 5" drill pipe require a higher flow rate for ROP's between 0 and 60 m/hr, but past 60 m/hr the flow rate for 5" and 5 ½" drill pipe remain the same using gel sweeps.